Constraining Higgs boson properties using MCFM

EPP Seminar, U. Penn, 17 March 2015

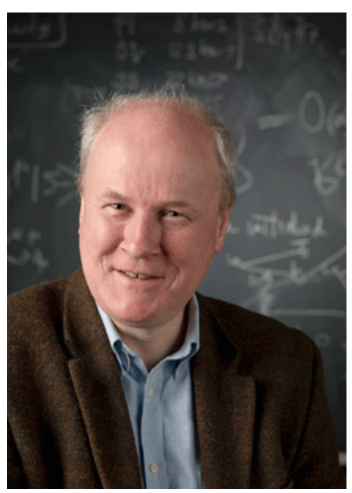
John Campbell

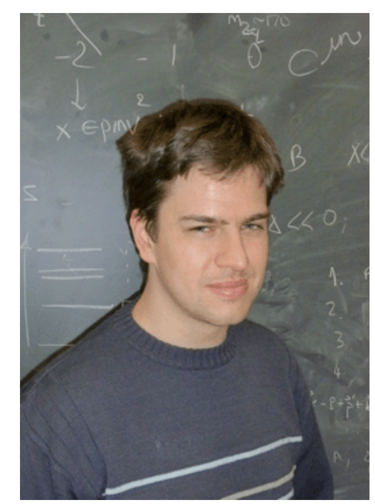
MCFM

★ MCFM = Monte Carlo for FeMtobarn processes: http://mcfm.fnal.gov

★ A parton-level Monte Carlo program that provides next-to-leading order predictions for a variety of Standard Model processes.

K. Ellis (FNAL) | C. Williams (Buffalo) | W. Giele (FNAL) | R. Röntsch (FNAL)



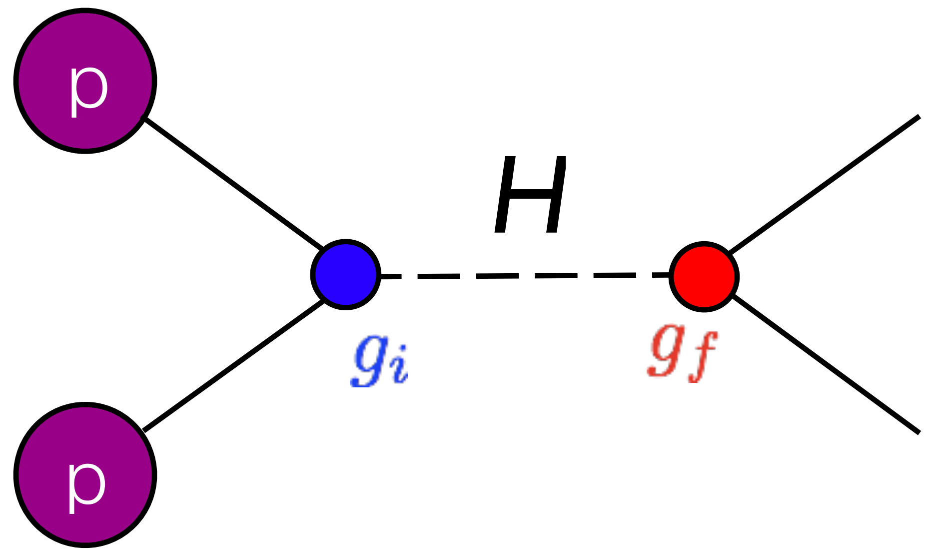
★ In this talk I will focus on developments in recent years aimed at helping to characterize Higgs boson properties: width and couplings to W and Z.

arXiv: 1311.3589, 1312.1628, 1409.1897, 1502.02990

Cross sections to parameters

★ Key question: how to go from measurements to parameters in the Lagrangian.

★ First pass, appropriate for data collected so far, simple parametrization that just scales SM couplings.



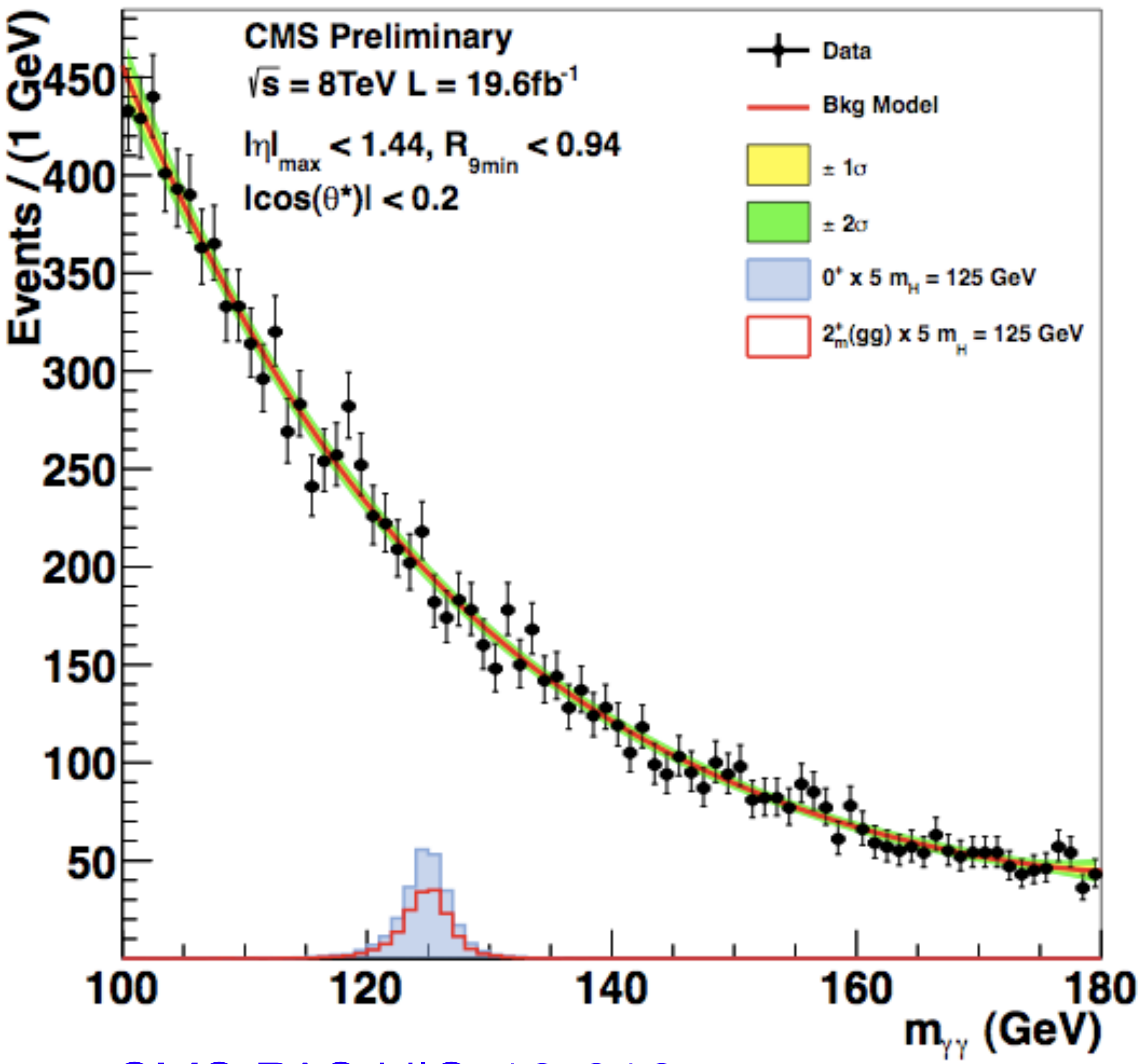
★ Total cross section depends on the strengths of the couplings of the Higgs boson in its initial production and final decay stages g_i and g_f and also on the width:

$$\sigma_{i \to H \to f} \sim \frac{g_i^2 \, g_f^2}{\Gamma_H}$$

★ How can these be disentangled to avoid degeneracy? Can width be probed?

Direct width constraints

★ How can we probe a SM width of 4 MeV at the LHC?



CMS PAS HIG-13-016

- Intrinsic detector resolution is of order a few GeV in the most well-measured channels.
- Limits inherently weak, e.g. CMS:

$$\Gamma_H < 6.9 \text{ GeV}$$
$$(95\% \text{ confidence})$$
$$(\Gamma_H \lesssim 1600\,\Gamma_H^{SM})$$

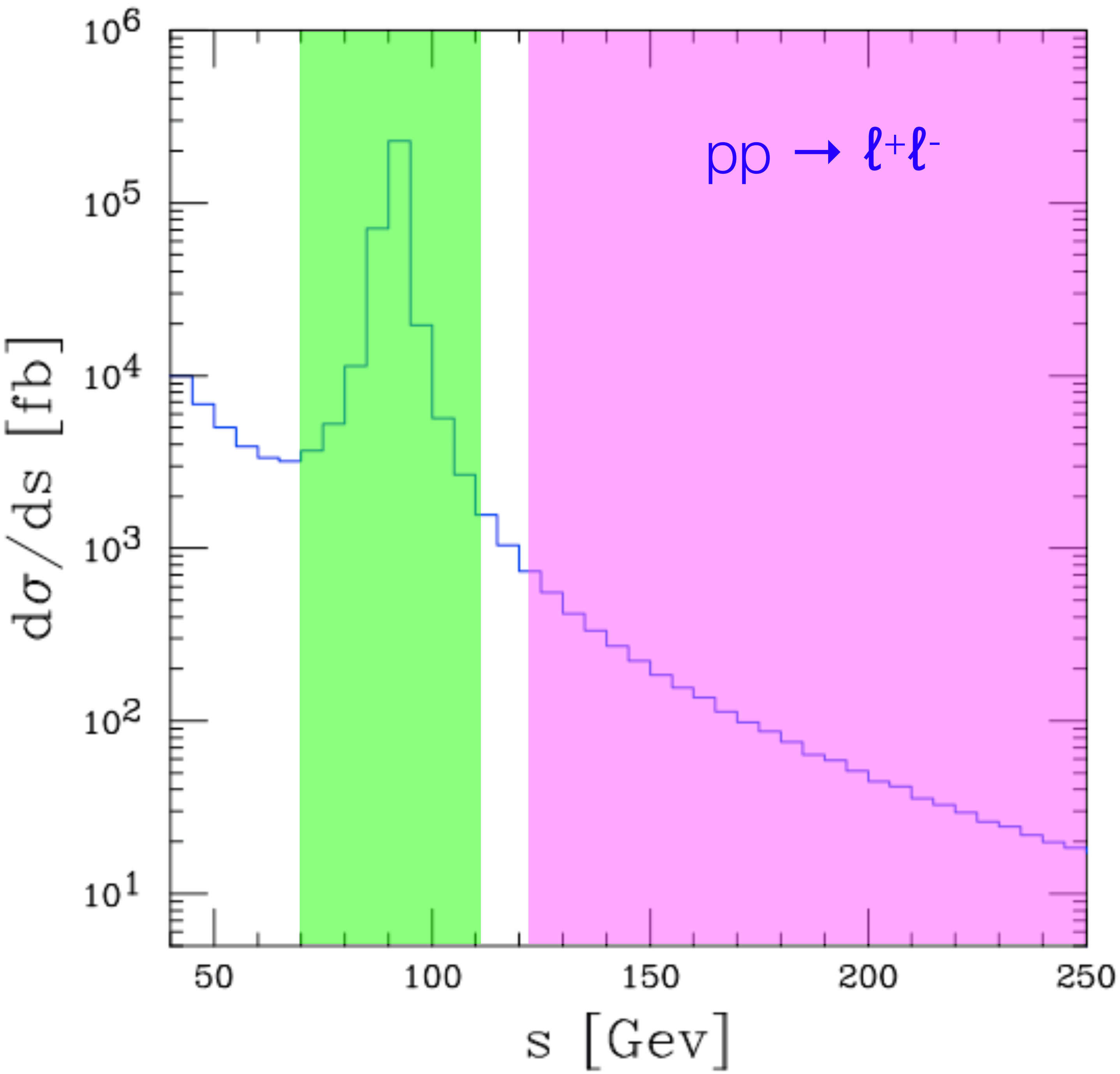
- Assume bound scales with statistics, combine with ZZ channel, 3000 fb^{-1}:

$$\Gamma_H \lesssim 200 \text{ MeV} \quad (\sim 50\,\Gamma_H^{SM})$$

The Caola-Melnikov method

(essence of 1307.4935)

★ Consider the Drell-Yan process. Can map out the resonance as a function of the four-momentum squared (s) that appears in the propagator.



- "On-shell" cross section in resonance region:

$$\sigma_{\mathrm{on}} \sim \int \frac{\mathrm{d}s}{(s-m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \propto \frac{1}{\Gamma_Z}$$

- "Off-shell" cross section above the resonance:

$$\sigma_{\mathrm{off}} \sim \int_{s \gg m_Z^2} \frac{\mathrm{d}s}{(s-m_Z^2)^2 + \cancel{\Gamma_Z^2 m_Z^2}}$$

(approx.) independent of width.

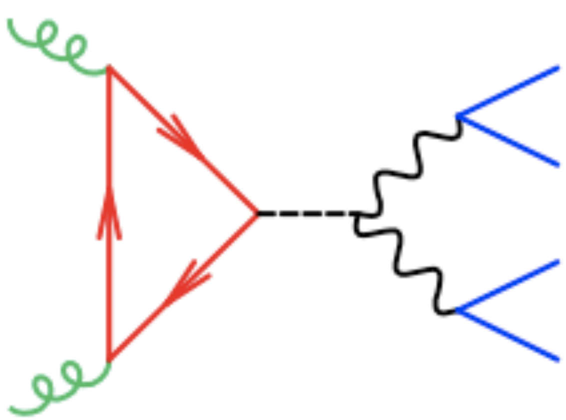
$$\Gamma \propto \frac{\sigma_{\mathrm{off}}}{\sigma_{\mathrm{on}}}$$

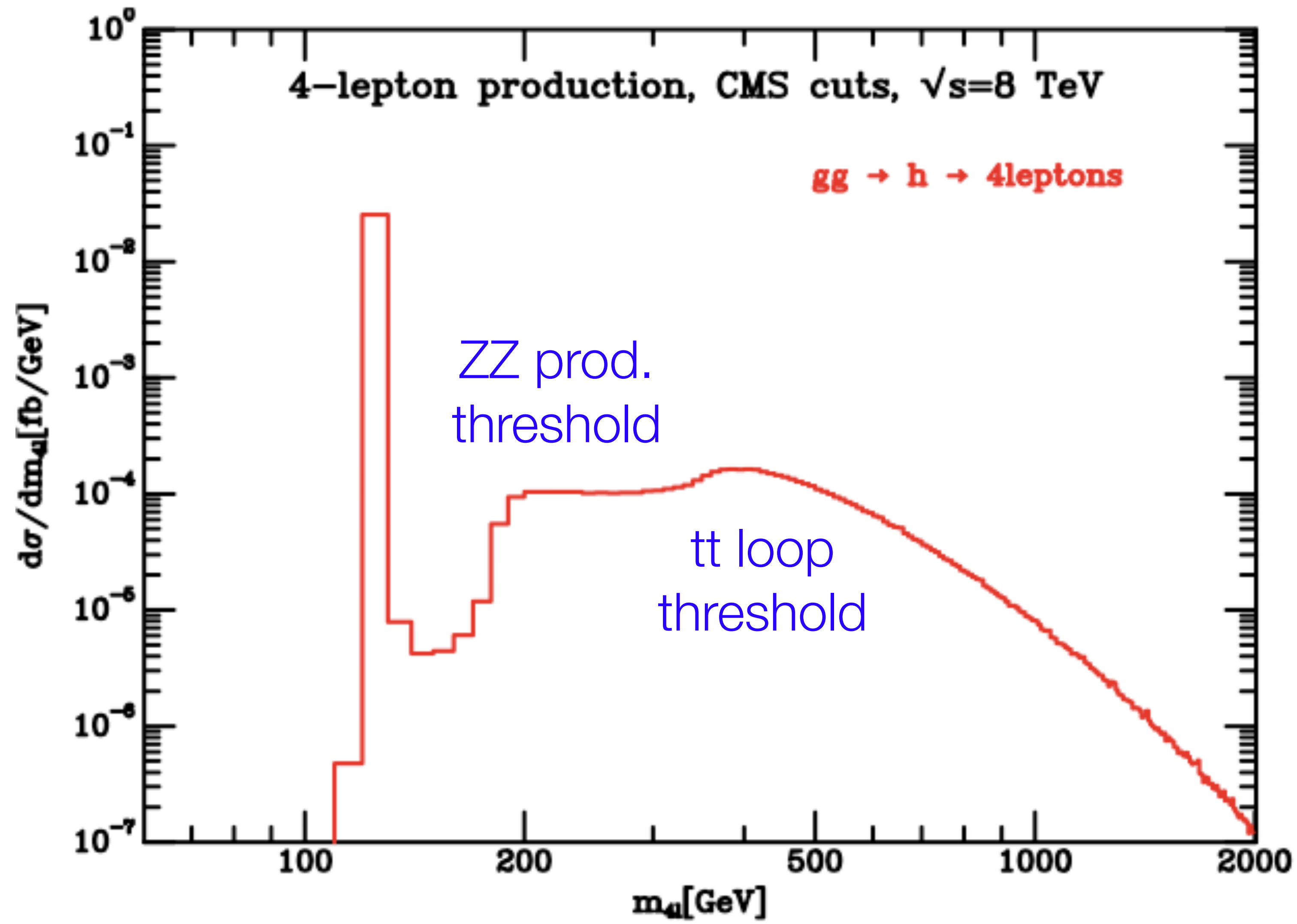
The Higgs golden channel

★ Naive expectation: $\Gamma_H/m_H \sim 10^{-5}$; resonance peak so narrow that there is no off-shell cross section to measure.

★ This is spectacularly wrong for the golden channel.

$$p + p \to H \to ZZ$$
$$\quad \hookrightarrow \mu^- + \mu^+$$
$$\quad \hookrightarrow e^- + e^+ \,.$$



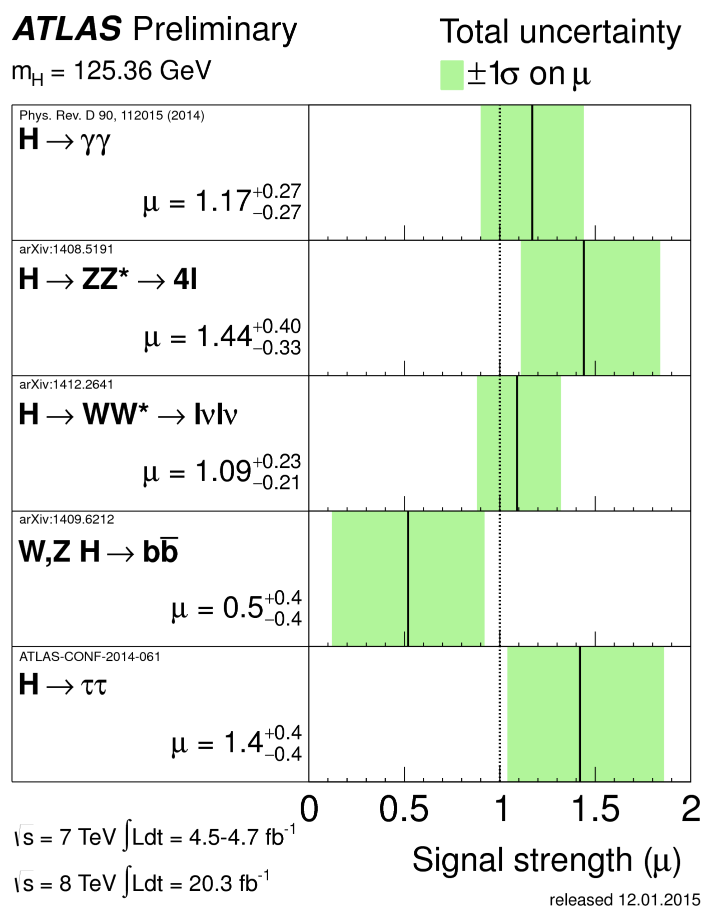


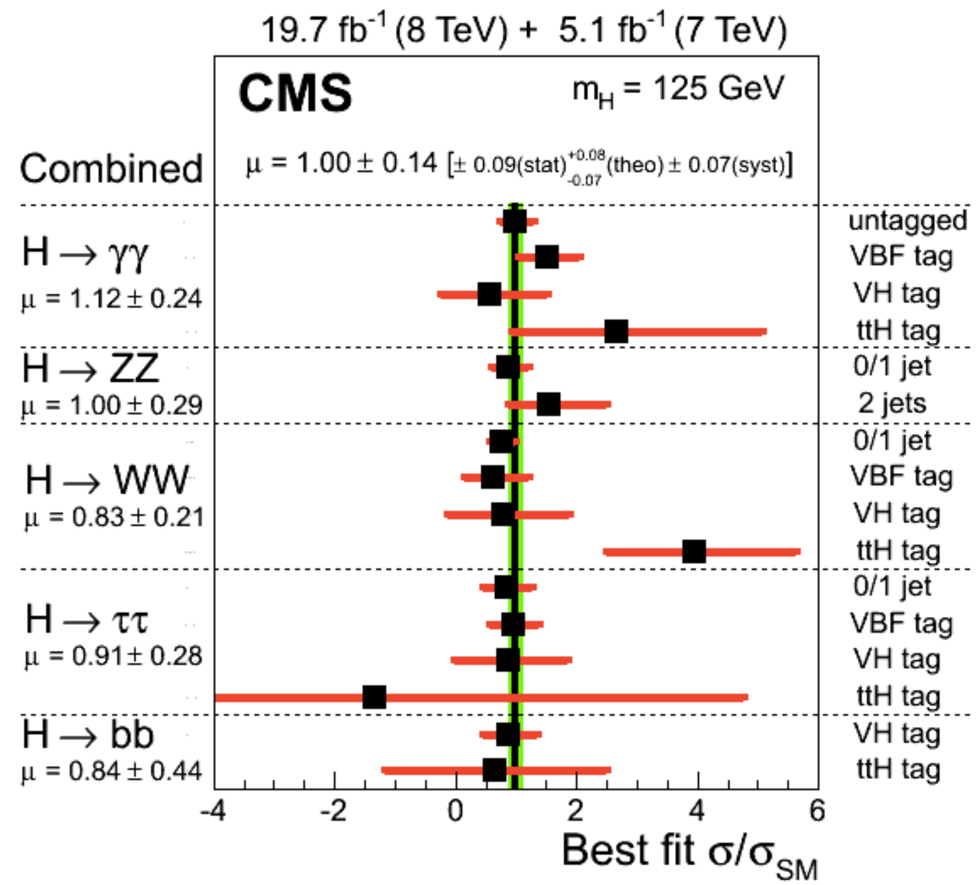
★ About 15% of the total cross section lies in the region with $m_{4\ell}$ > 130 GeV.

Kauer, Passarino, 1206.4803

Strategy

★ We know that the peak cross-section is in good agreement with SM expectation.





★ Fixing the on-shell cross-section to the SM value means that a larger Higgs boson width leads to more off-shell events.

$$\Gamma \propto \frac{\sigma_{\rm off}}{\sigma_{\rm on}}$$

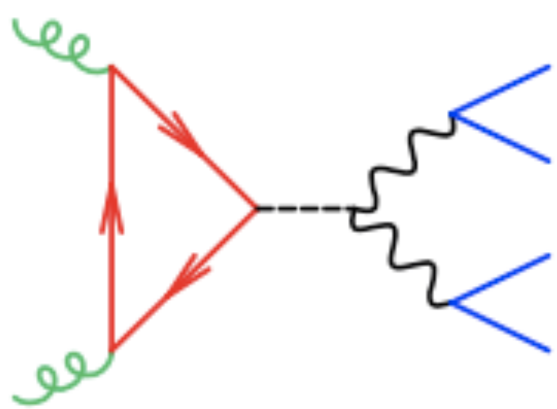
★ Need precise prediction for H→4-leptons to turn measured rate into a constraint.

Calculation and results

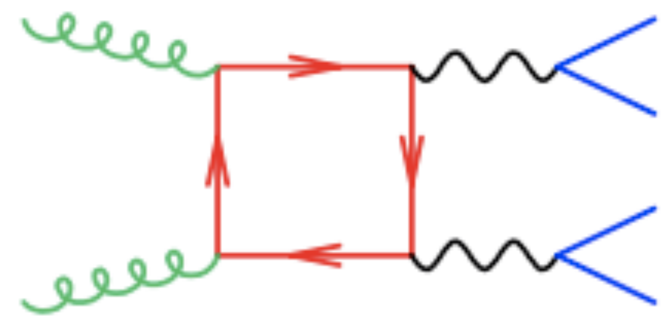
4-lepton production diagrams

★ Not just the Higgs boson diagrams leading to 4-lepton final state!

Higgs

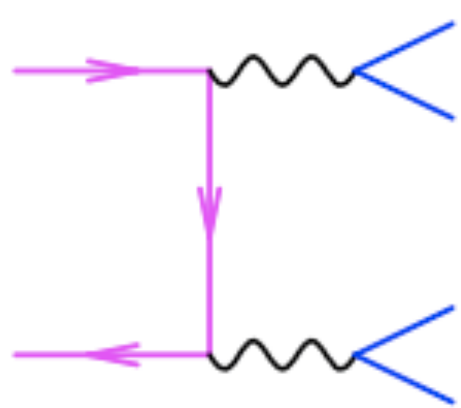


(a)



(b)

SM background



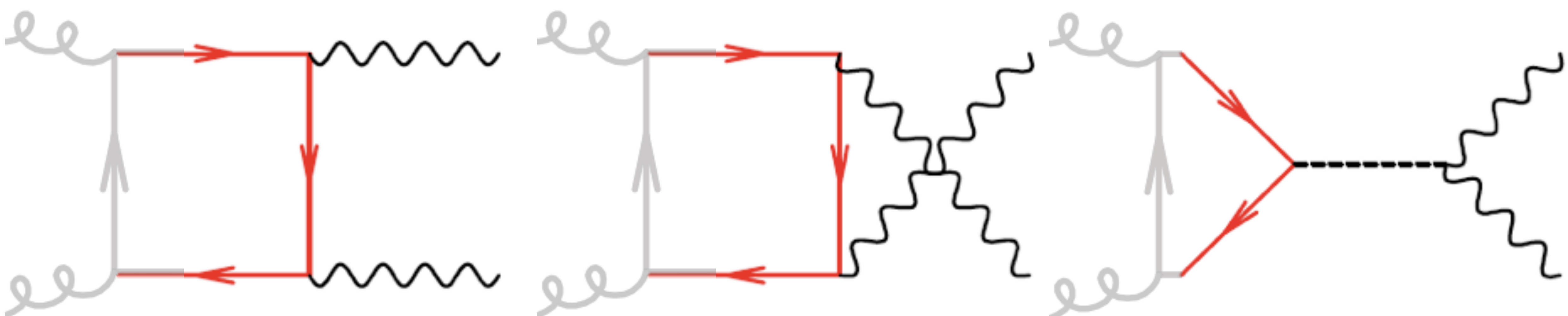
(c)

gg→ZZ →4l box

Importance of interference

★ Usual classification into "signal" and "background" contributions neglects the effect of interference, which is particularly important since a Higgs boson is involved.

★ Consider high-energy $t\bar{t} \to ZZ$ scattering (diagrams embedded in loops), where it is straightforward to examine behavior using longitudinal modes of Z's.



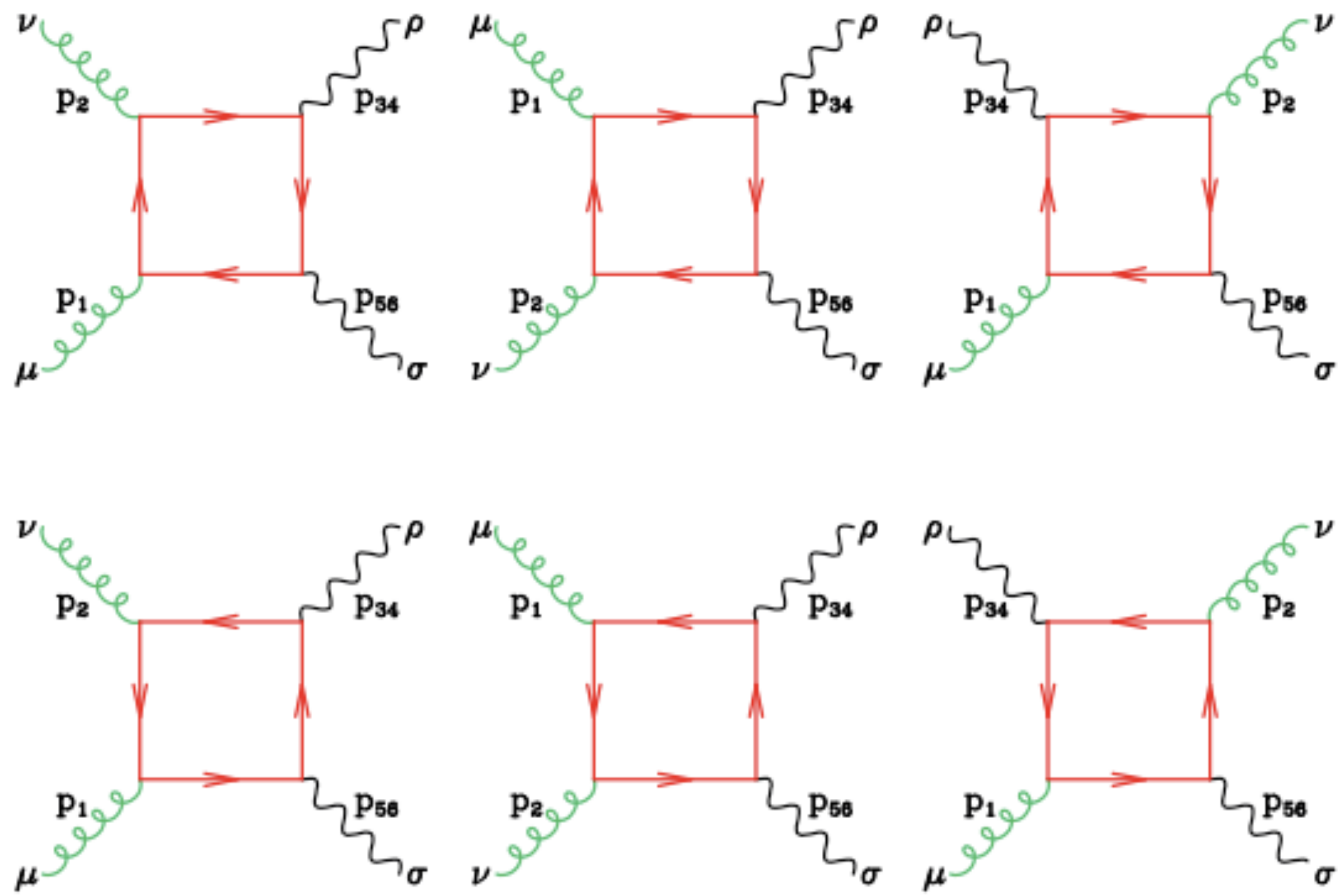
$aE^2 + (b+c)m_t E$ $\quad$ $-aE^2 + (d-c)m_t E$ $\quad$ $-(b+d)m_t E$

★ Inclusion of Higgs diagram essential to cancel bad high energy behaviour; observation of this mechanism would be evidence of the Higgs boson doing its job.

★ Destructive interference weakens bound: $\sigma_{\rm off}/\sigma_{\rm on} \approx a\,\Gamma - b\sqrt{\Gamma}$

Calculation

- ★ Most challenging calculation is the gg→ZZ box diagrams.
- ★ Essential to account for quark masses in the loop to obtain correct high-energy behaviour.
- ★ A long and rich history of such calculations.
- ★ Original calculation using dispersive techniques in 1971!



Constantini, de Tollis, Pistoni; Nuovo Cim. A2 (1971)

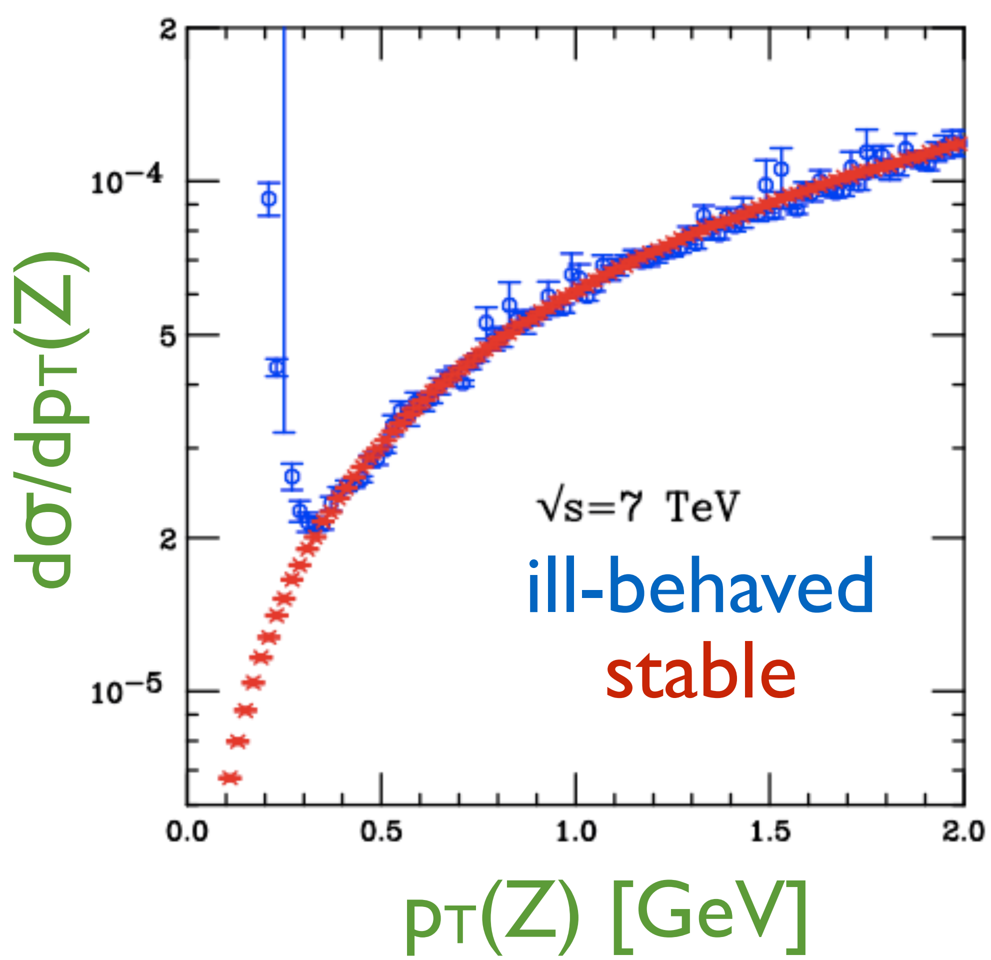
- ★ More recently, implementation of all contributions numerically in `gg2VV` code.

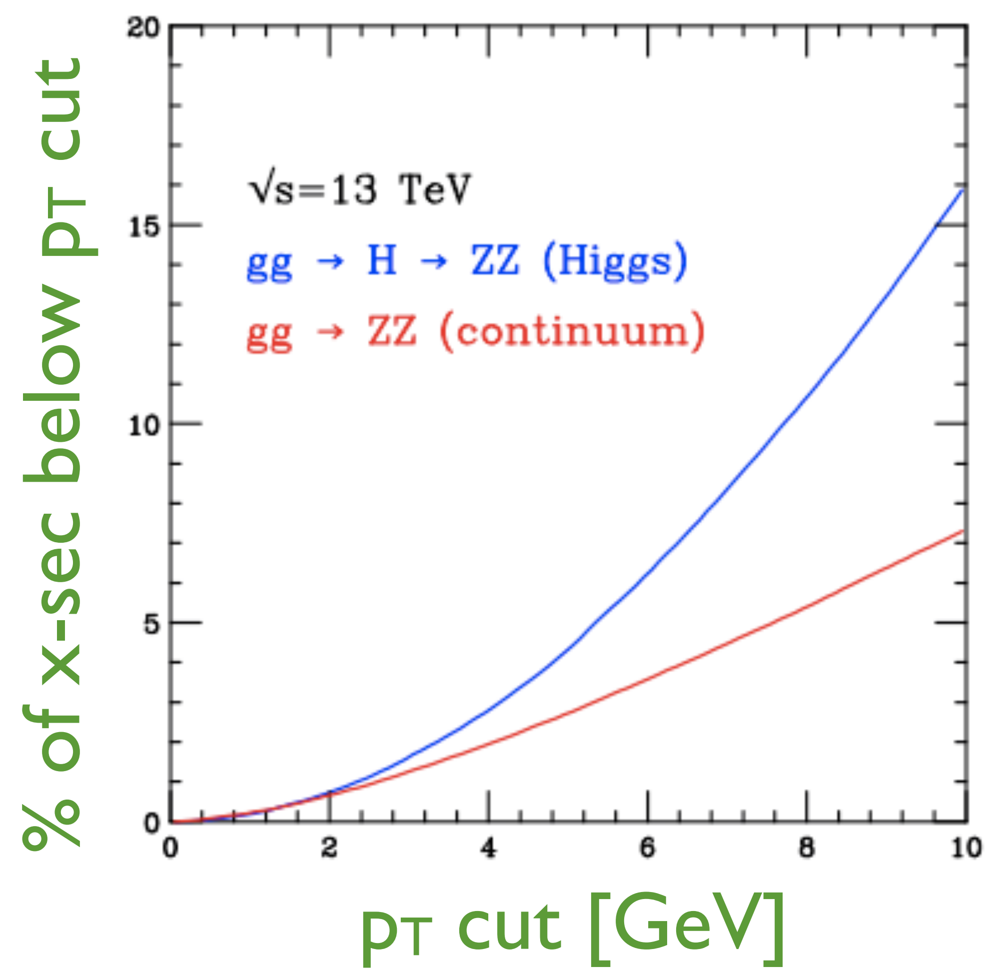
  Kauer, Passarino; 1206.4806

- ★ MCFM: full analytic calculation for fast and numerically-stable evaluation.

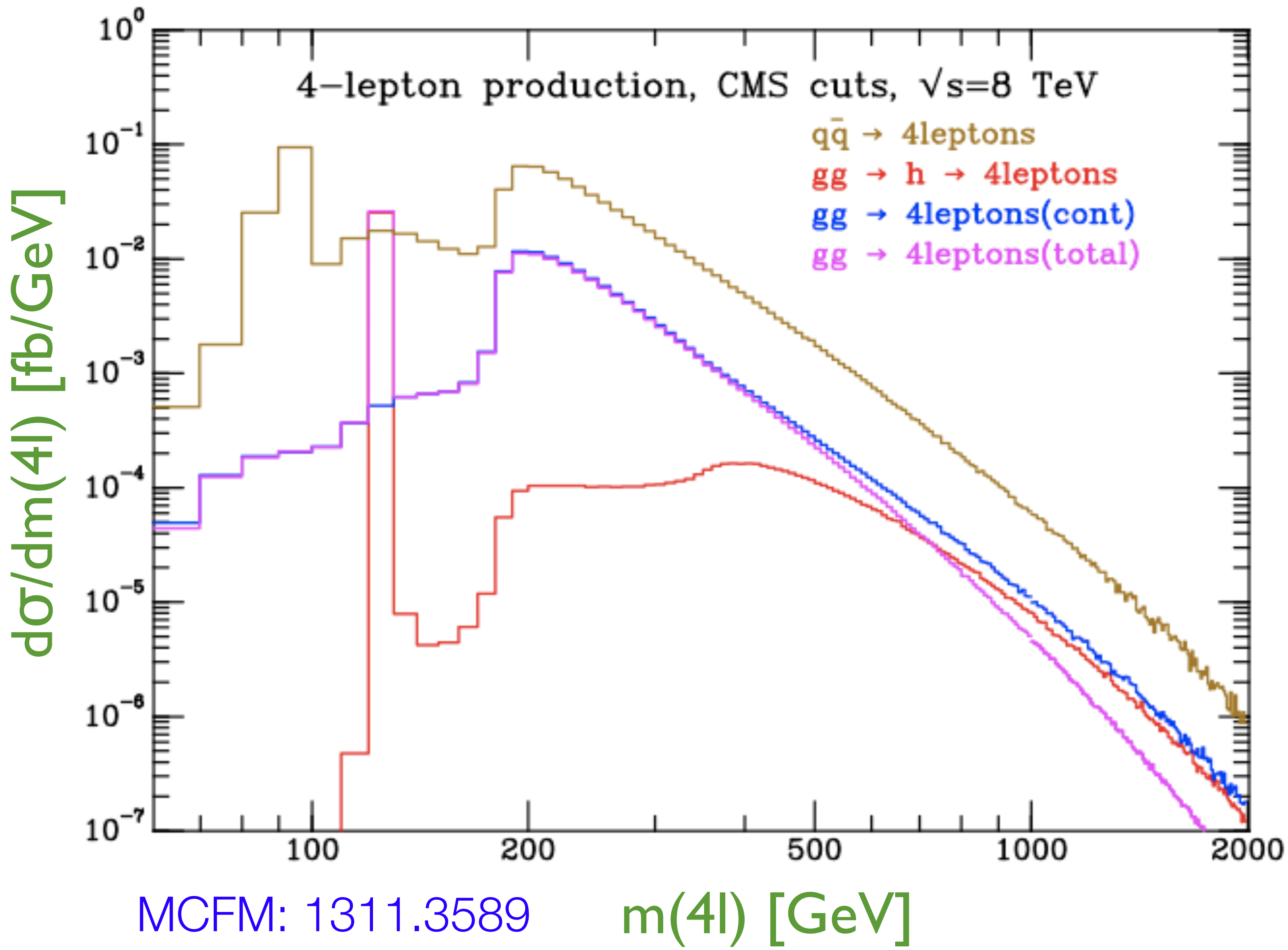
Stability

- ★ Matrix elements suffer from numerical instability as $p_T(Z) \to 0$ even though they are completely finite in that limit.
- ★ Important to ensure that implementation is stable there since a fairly substantial contribution to the total cross section comes from the low p_T region.





The big picture



MCFM: 1311.3589

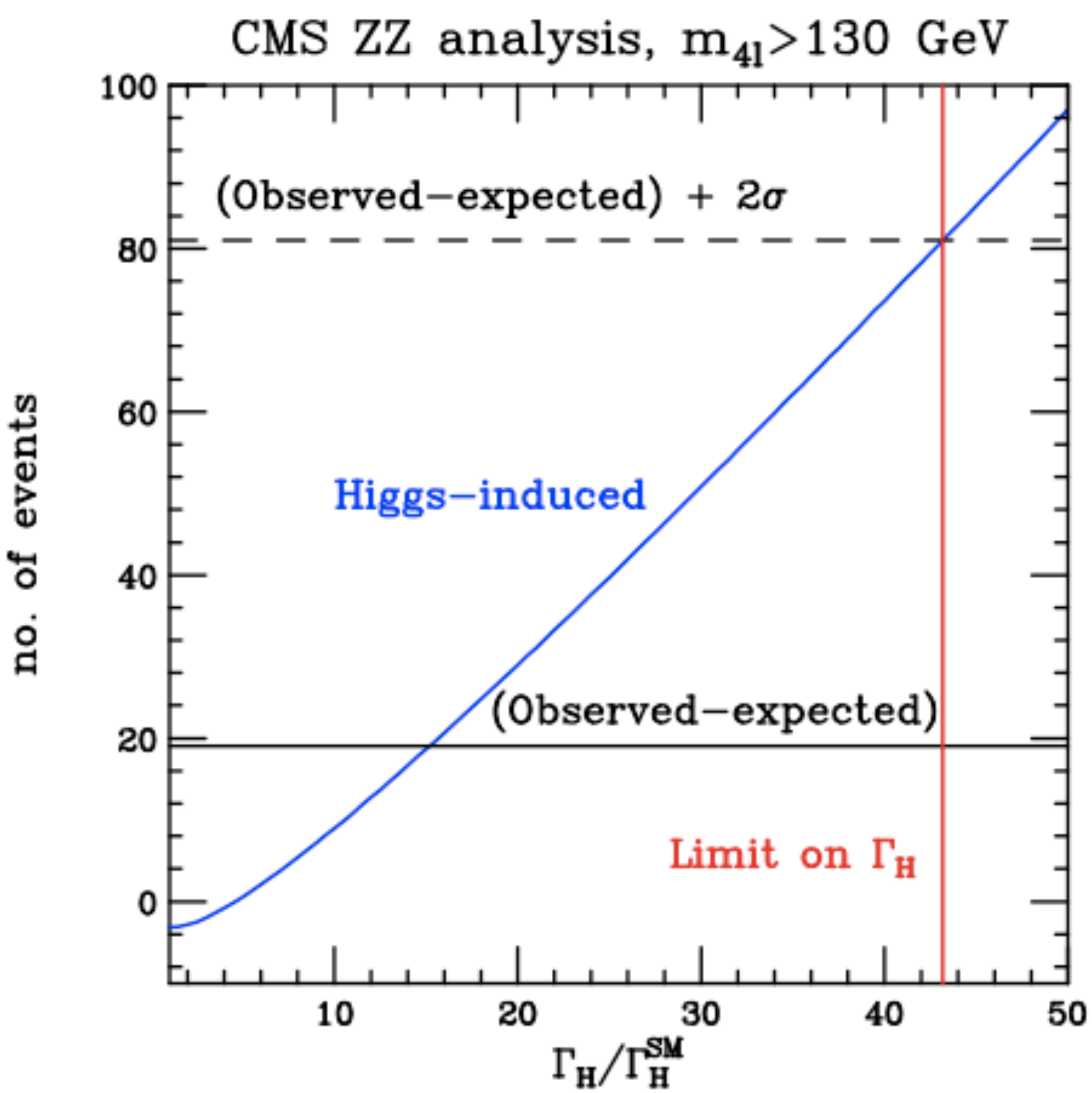
★ Continuum ($q\bar{q}$) background 1-2 orders of magnitude larger throughout most of range.

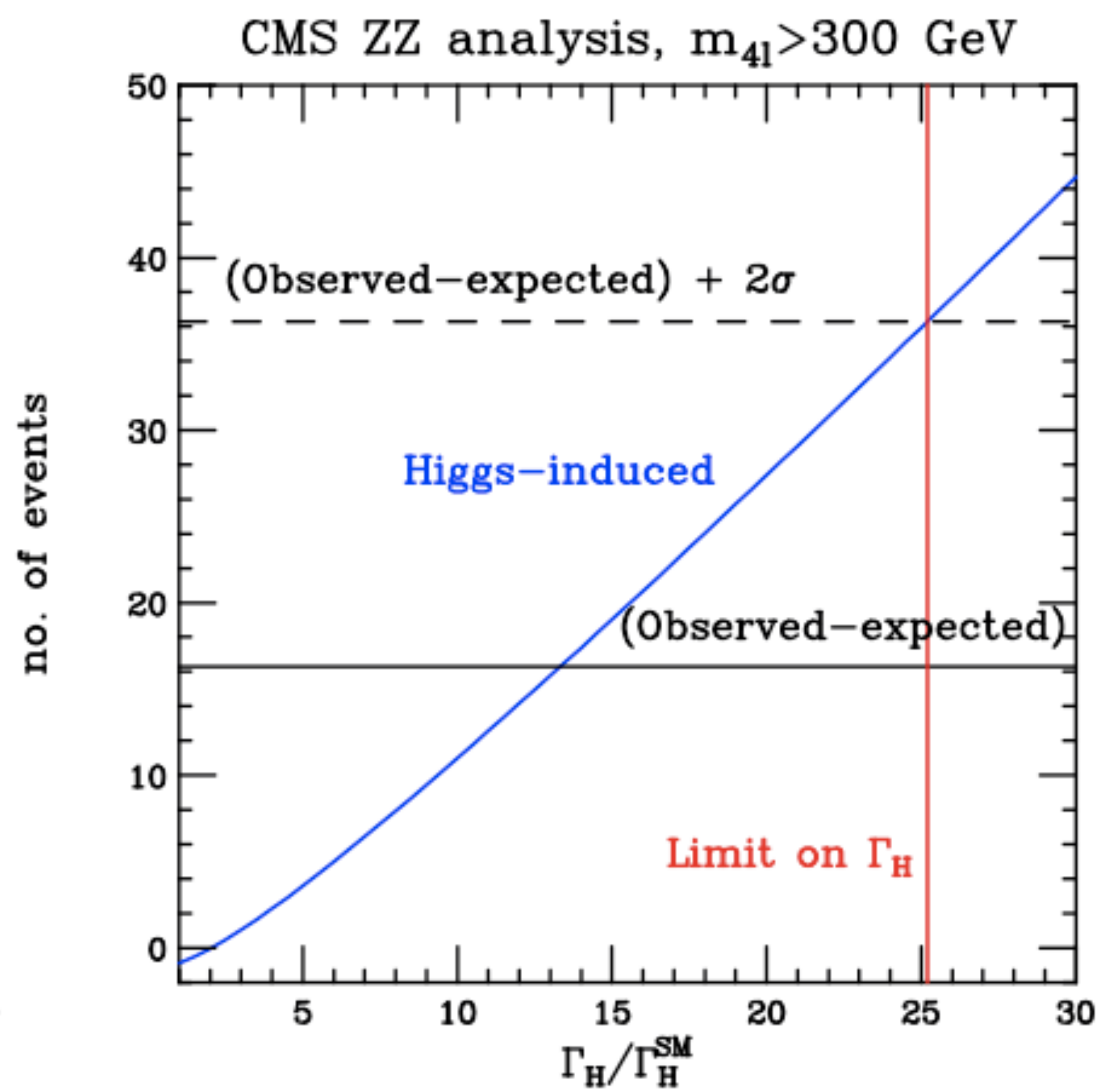
★ Destructive interference clear for m_{4l} >400 GeV.

★ Cannot describe off-peak region without proper treatment of interference.

★ Difficult to observe effect (in the SM) since strong pdf suppression, so little rate.

Theorists' estimate





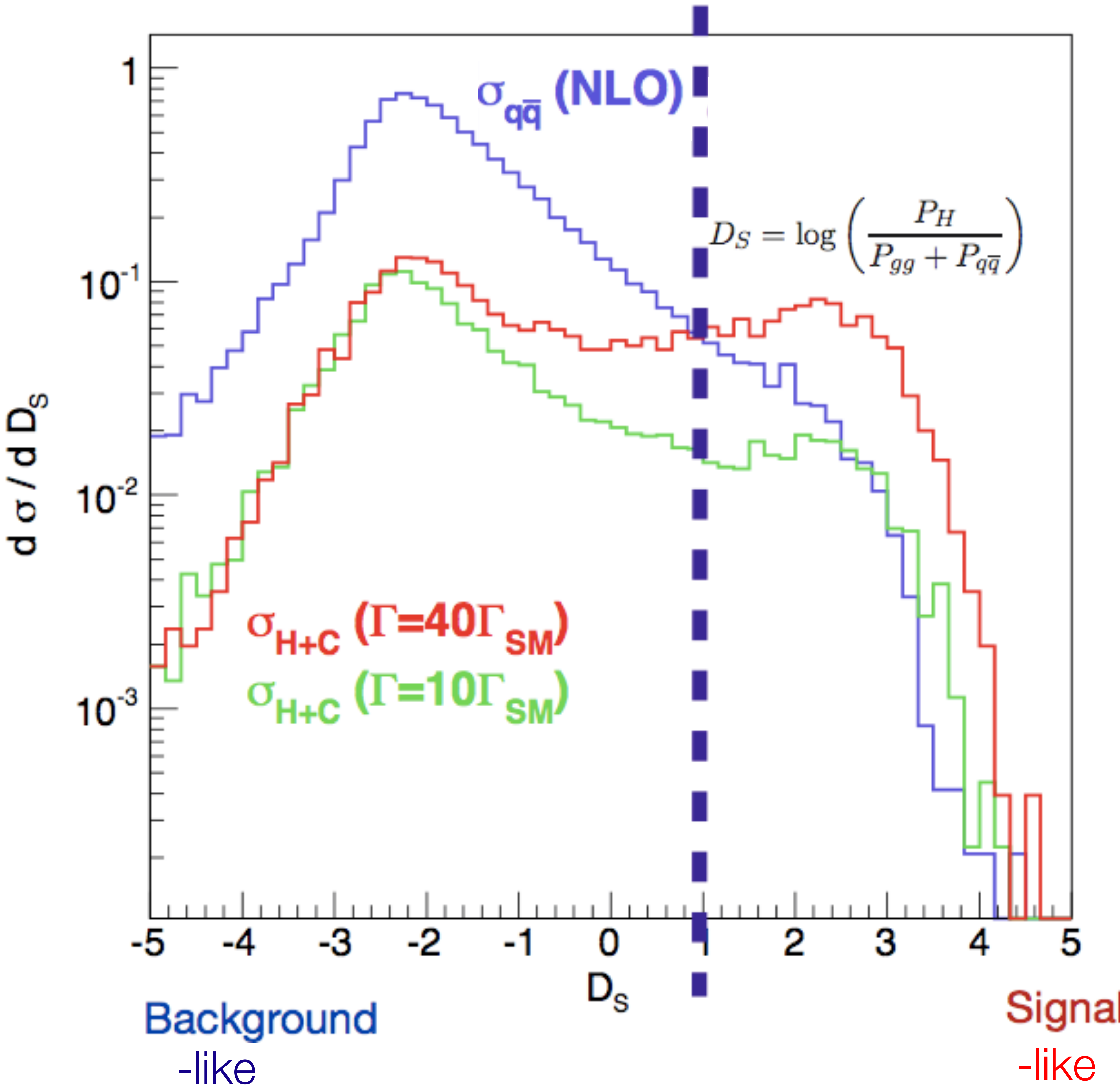
expected (no H): 432 ± 31

$$\boxed{\Gamma_H < 43.2\,\Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}}$$

expected (no H): 71 ± (10?)

$$\boxed{\Gamma_H < 25.2\,\Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}}$$

Matrix element method



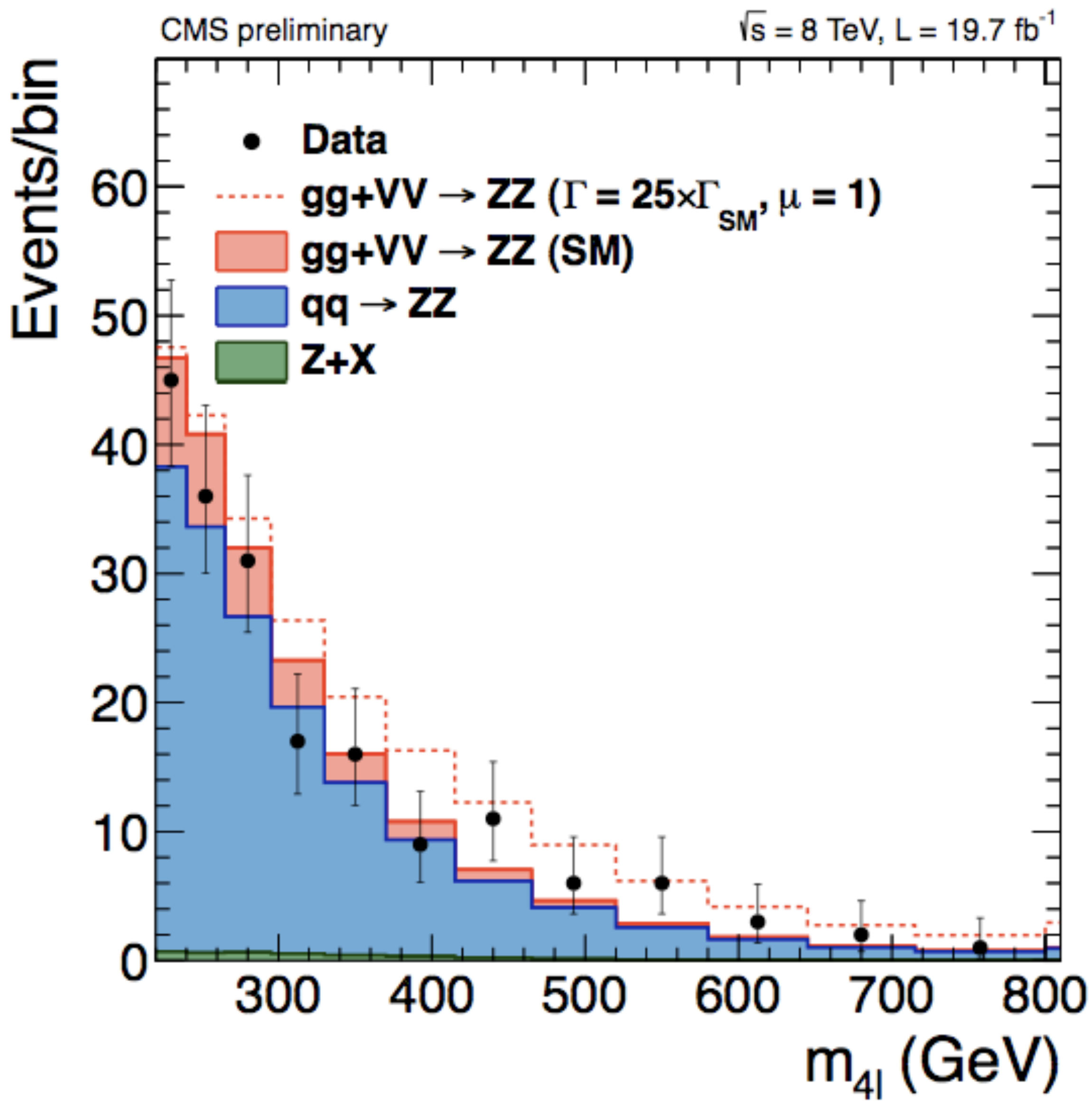
- ★ Use MCFM to compute discriminant that isolates gluon-related contributions that are sensitive to width.
- ★ Using an analysis that roughly mimics the CMS results found before, bound can be improved:

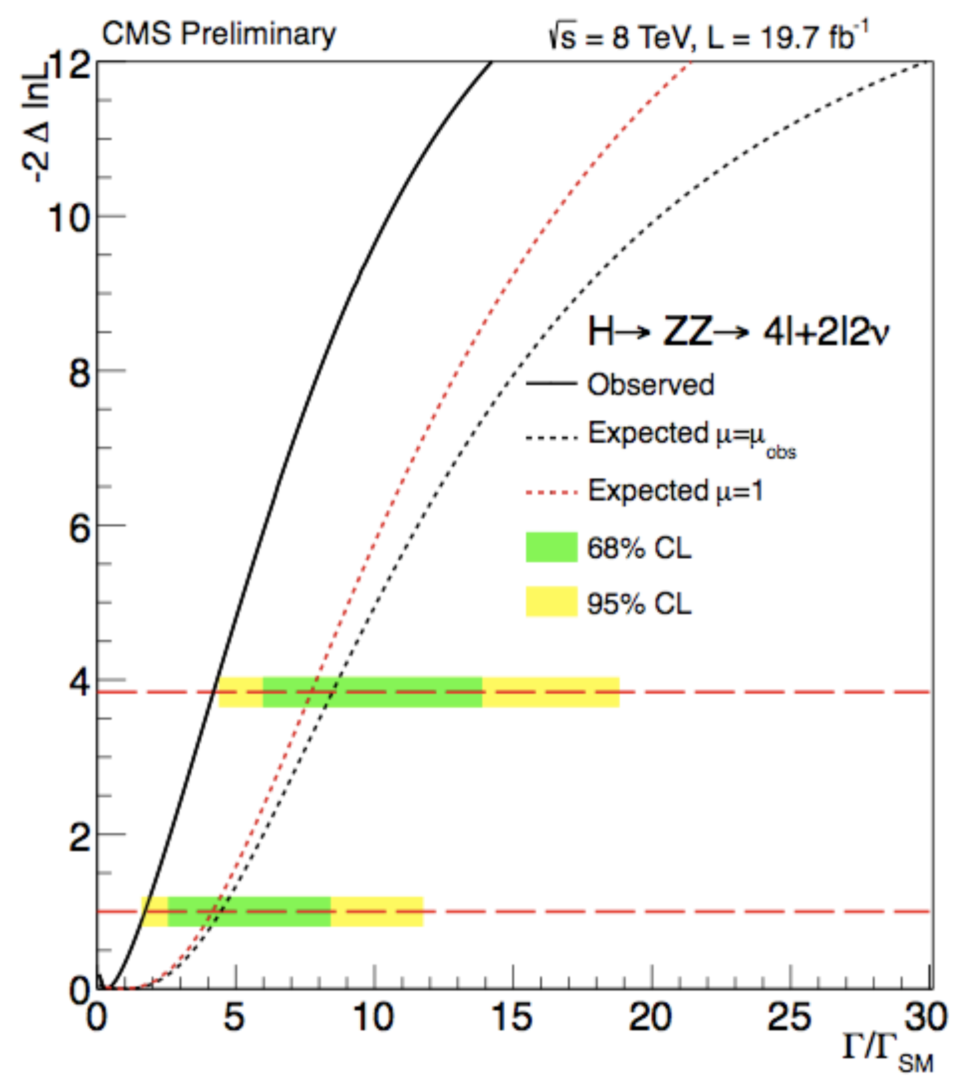
$$\boxed{\Gamma_H < \left(15.7\ {}^{-2.9}_{+3.9}\right)\ \Gamma_H^{SM} \text{ at } 95\% \text{ c.l.}}$$

- ★ This procedure adopted by ATLAS and CMS.

The CMS result

PAS HIG-14-002





$$\Gamma_H < 4.2 \times \Gamma_H^{SM} \text{ at 95\% confidence}$$

The WW channel

★ The ZZ channel is convenient: well-measured leptons allow the Higgs boson lineshape to be mapped out and peak/off-shell regions directly identified.

★ However, exact mapping of lineshape is not crucial, just need well-separated regions corresponding to on- and off-resonance.

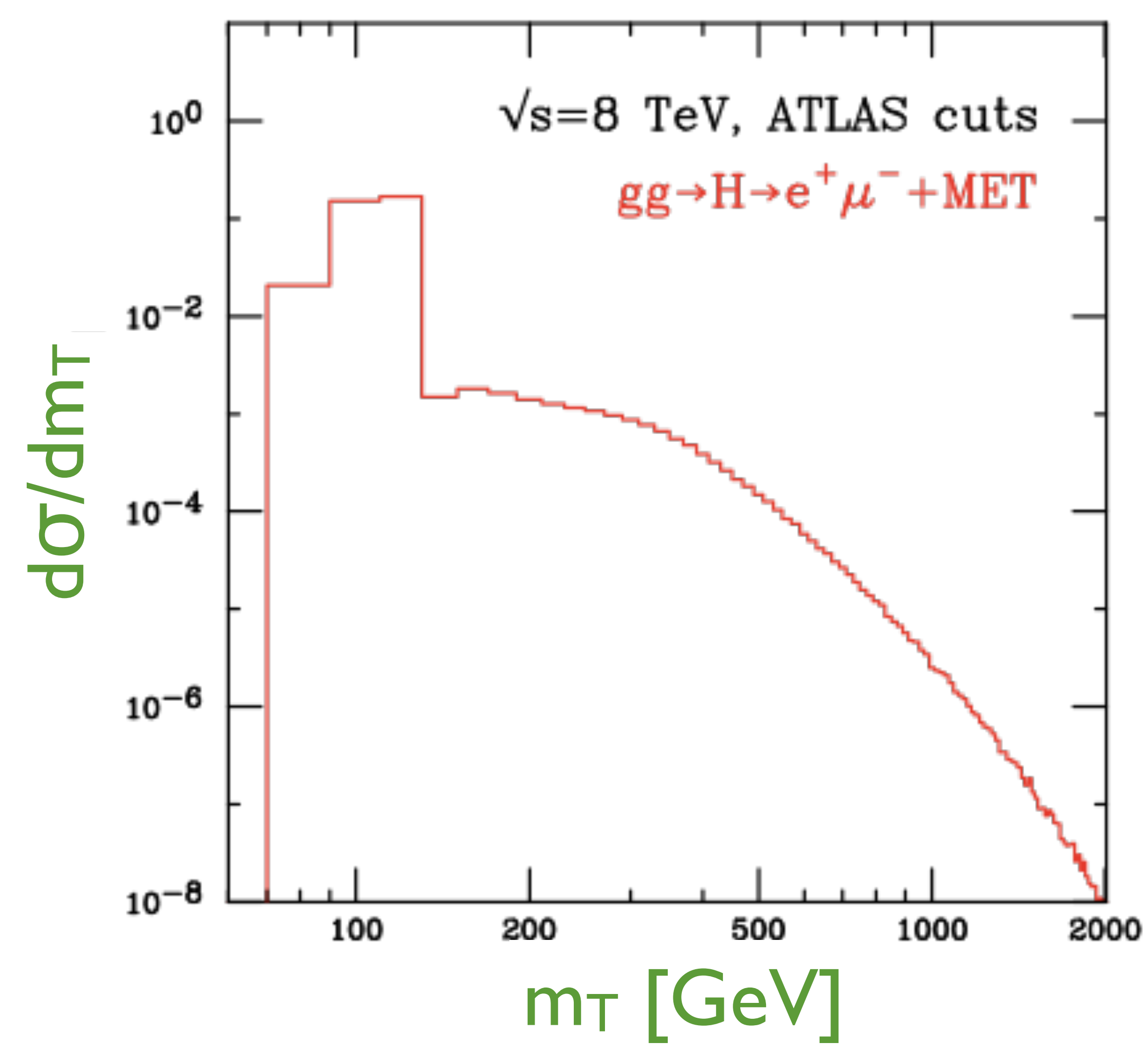
★ Try to play the same game in WW channel:

$$gg \to W^+W^- \to e^+\mu^-\nu_e\bar{\nu}_\mu$$

★ As proxy for invariant mass, use transverse mass of WW system:

$$M_T^2 = (E_T^{miss} + E_T^{\ell\ell})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2$$

★ Some features washed out, but clear separation between peak and tail remains.



WW vs ZZ

★ Advantages:

- threshold for two real W's much closer than for two real Z's
- branching ratio into leptons also larger
- combined, two orders of magnitude more events:

$$\mathrm{Br}(H \to WW) \times \mathrm{Br}(W \to \ell\nu)^2 = 2.7 \times 10^{-3}$$
$$\mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to \ell^+\ell^-)^2 = 3.2 \times 10^{-5}$$

★ Disadvantages:

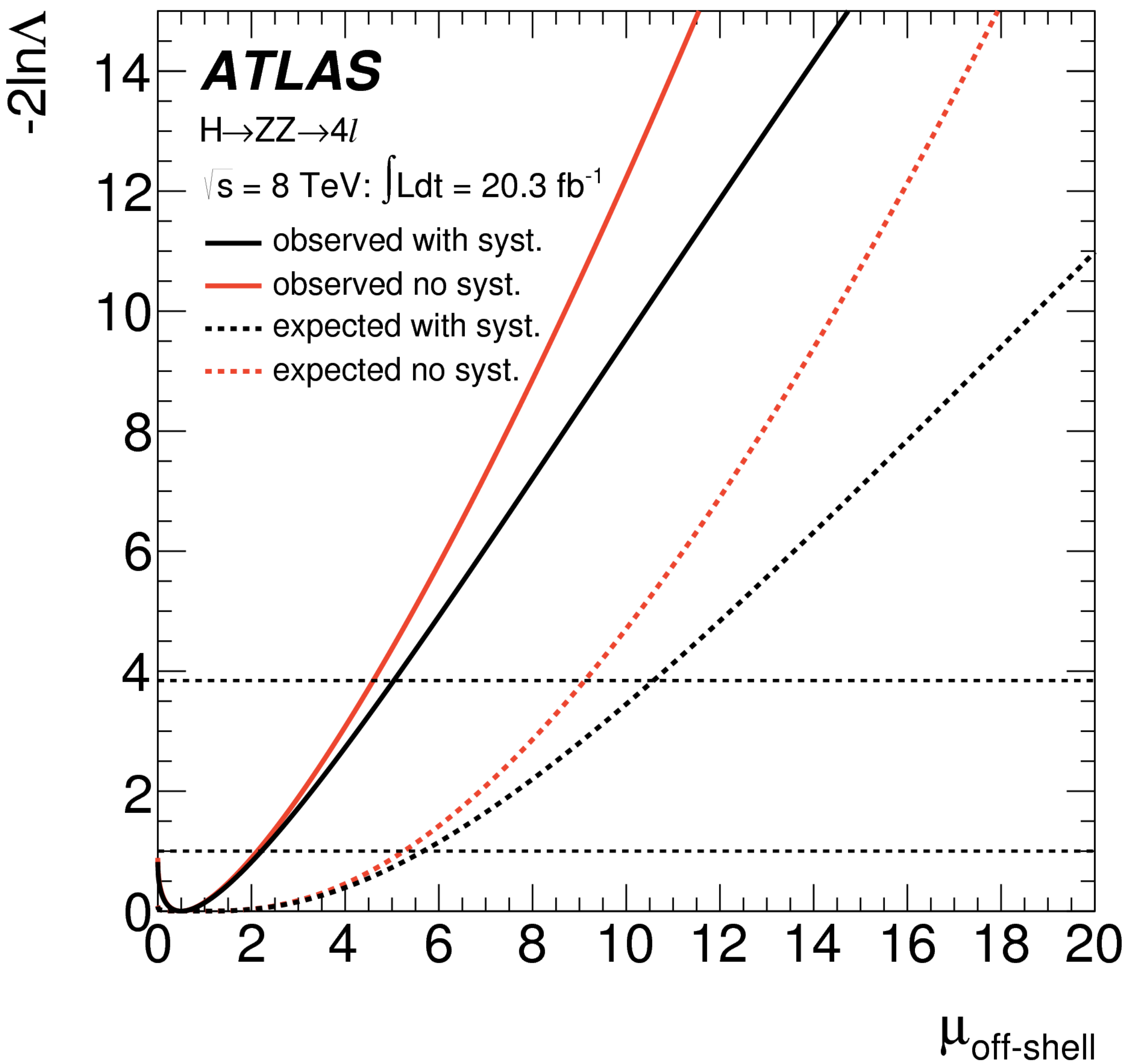
- much less clean so many more backgrounds, especially top-related ones that require a jet-veto to control
- even observing the on-shell Higgs boson in this channel is not easy.

Estimated sensitivity about a factor of three worse for WW than ZZ

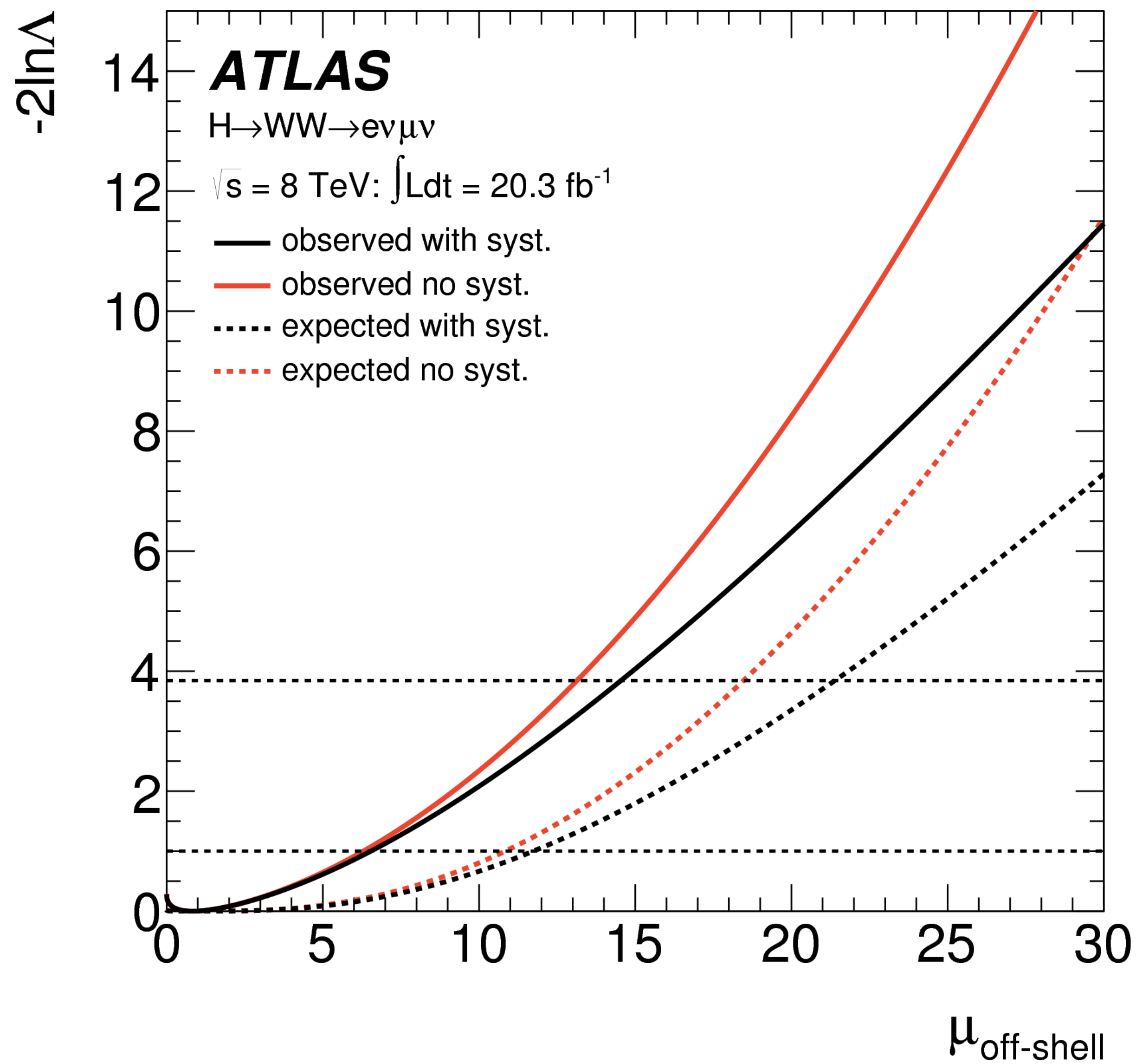
MCFM: 1312.1628

ATLAS comparison of ZZ, WW

arXiv: 1503.01060



ZZ



WW

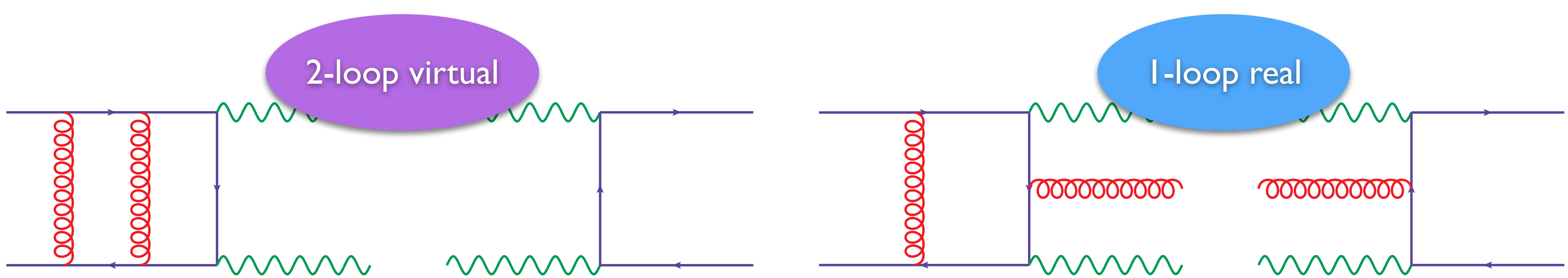
Caveat: higher orders

★ Despite the presence of a loop, the effect of the interference is computed at LO; however the Higgs contribution alone is known to (at least) NNLO.

★ Can assume the higher-order corrections to the interference scale in the same way, with some additional uncertainty (CMS strategy so far).

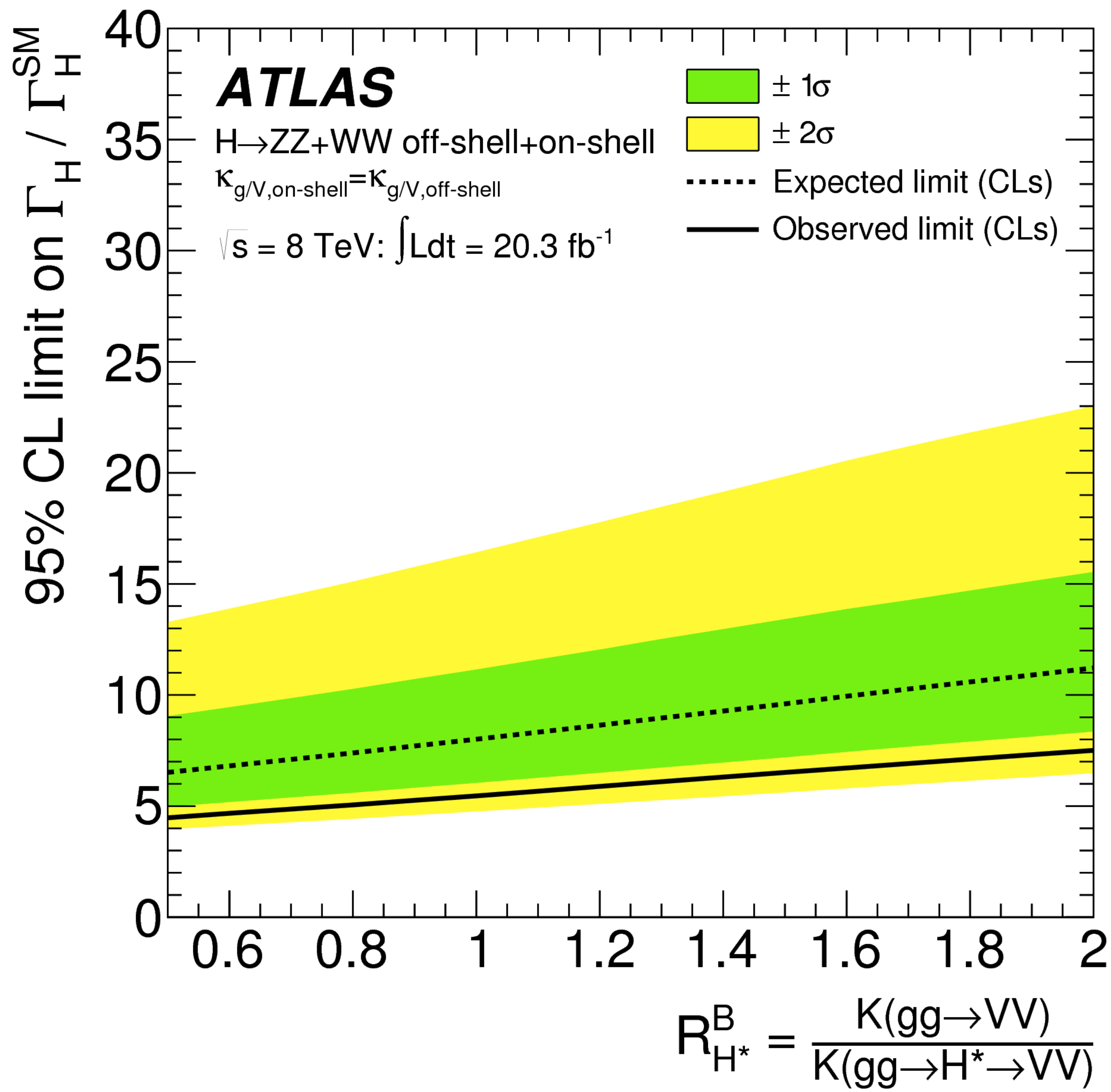
★ This is supported by soft gluon approximation of the NLO and NNLO result, which hints at a similar K-factor with perhaps a 30% uncertainty.

★ But we will only know for sure when the interference is calculated to NLO: i.e. 2-loop virtual and 1-loop real radiation contributions.



★ In the meantime, a good strategy is to consider full gg K-factor unknown.

ATLAS result vs. K-factor

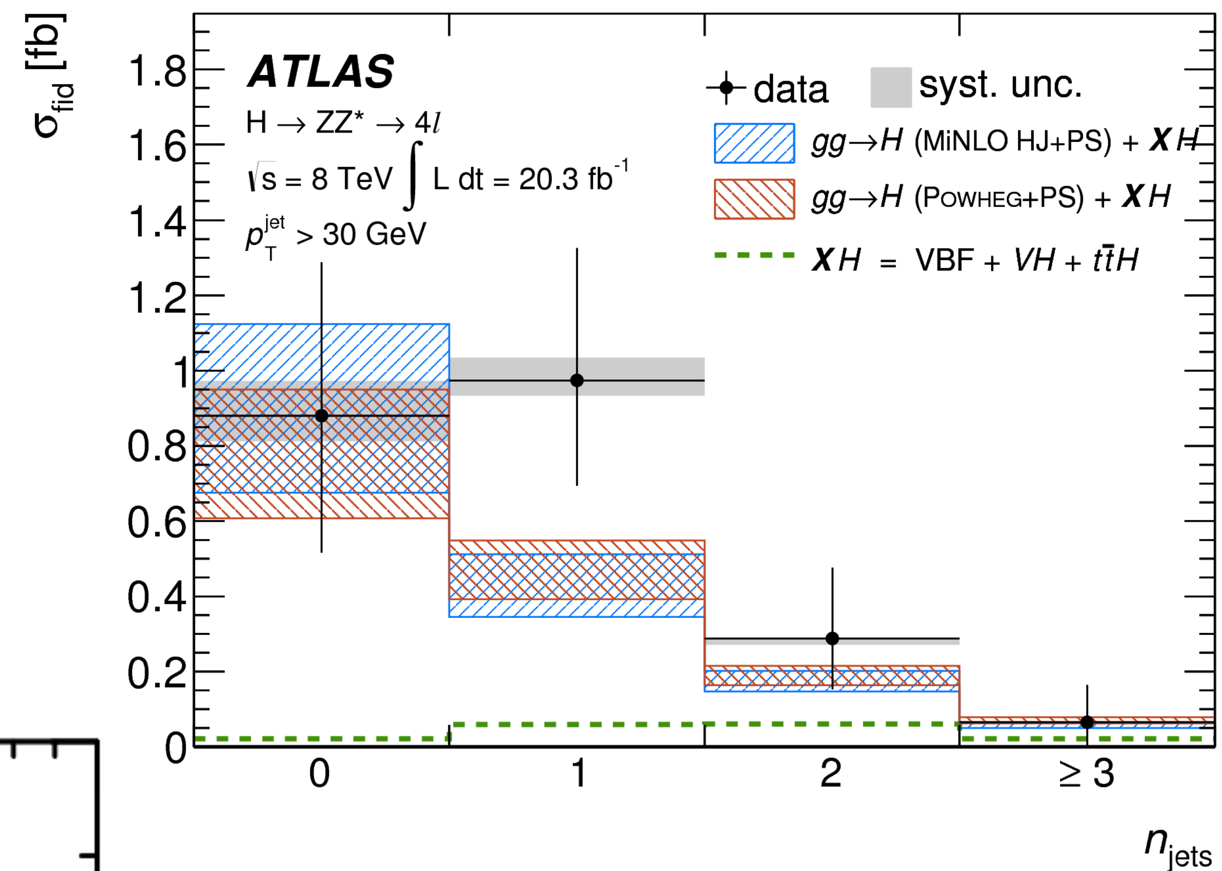


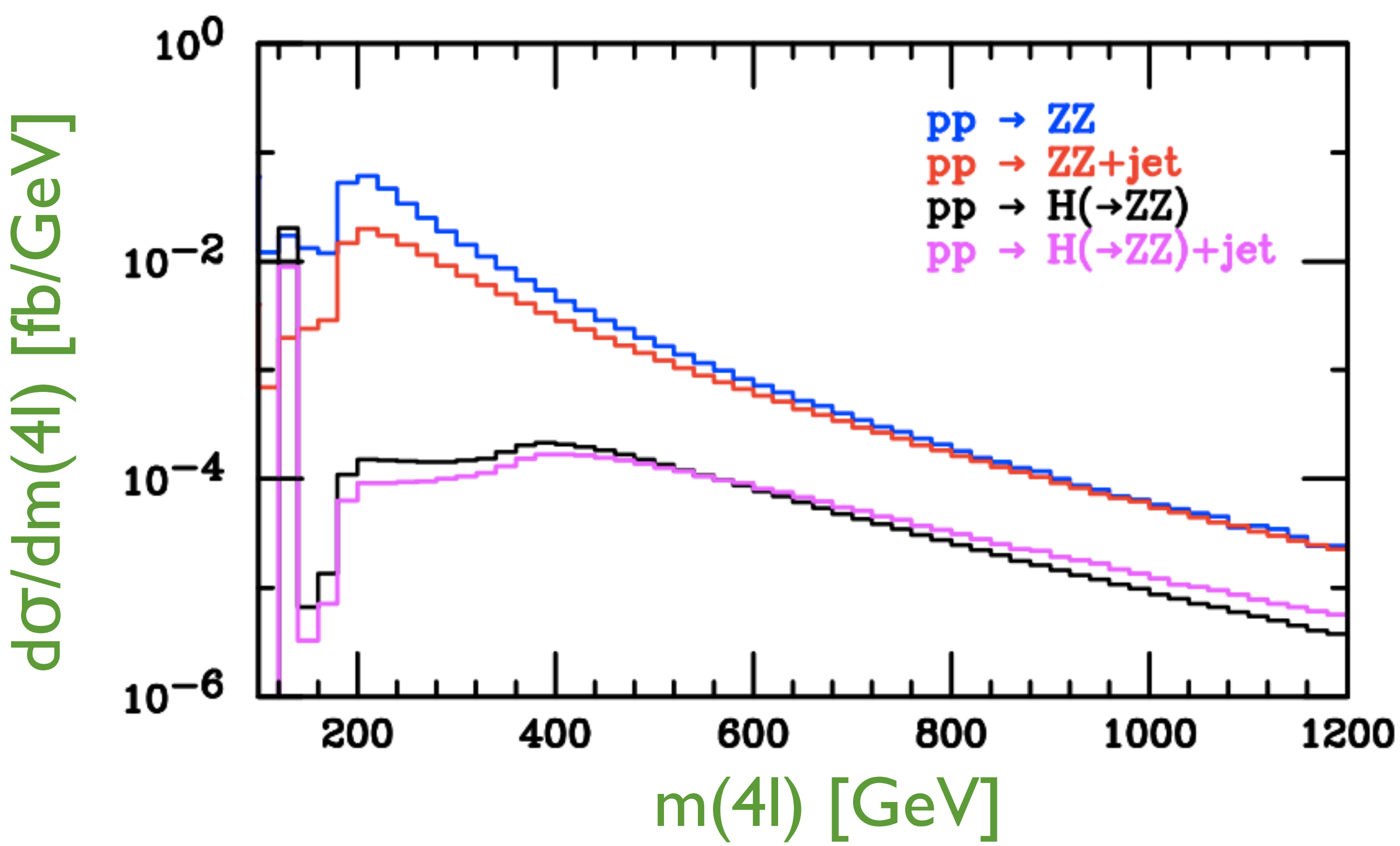
95% CL upper limit on Γ_H/Γ_H^{SM} in the range 4.5–7.5

Extension to other channels

What about Higgs+jets?

- ★ Production by gluon fusion means that there are a significant number of events where the Higgs boson is accompanied by hard jets.
- ★ Can the jet-binned cross-sections provide additional information?





- ★ For one jet, unequivocal yes!
- ★ Off-shell tail is about the same size, while leading SM background is smaller.

MCFM: 1409.1897

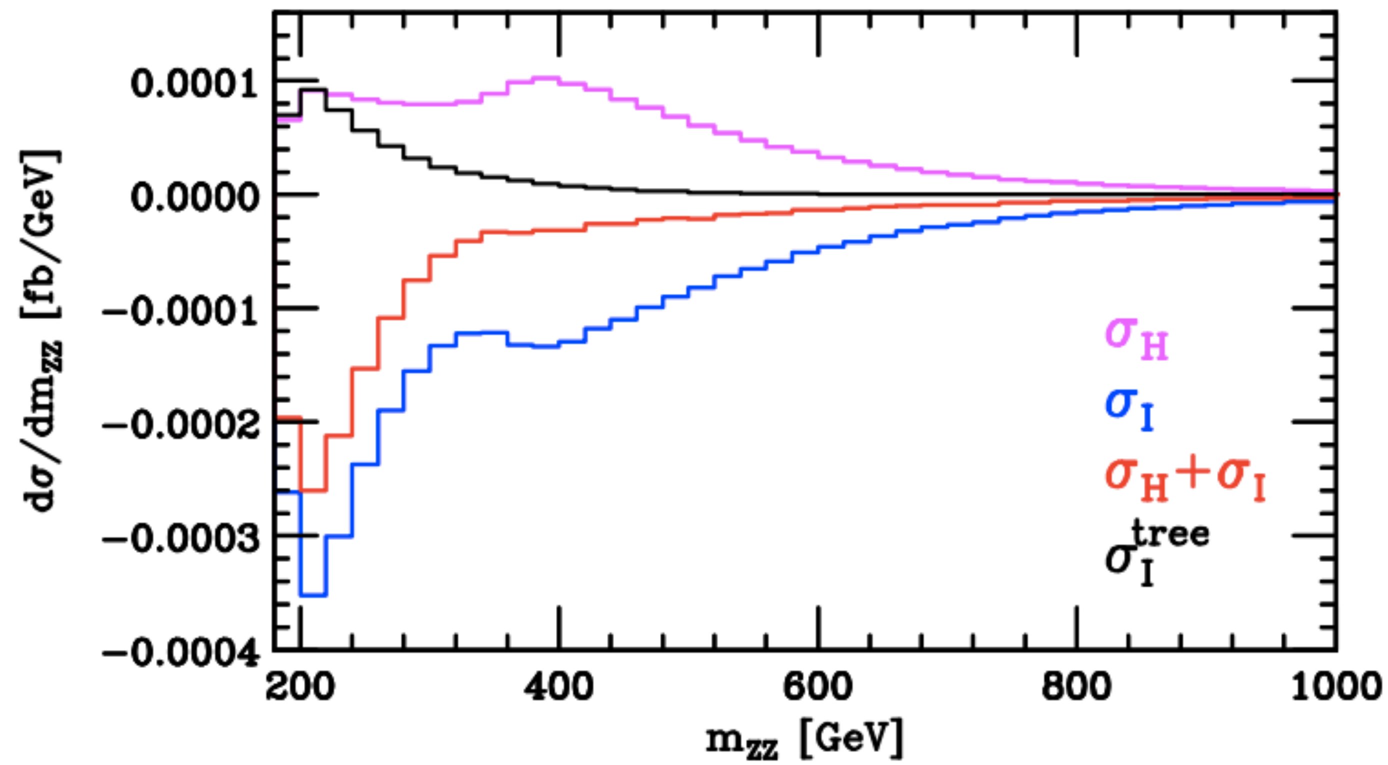
ZZ+jet results

- ★ Calculation very challenging even at one-loop; simplified by use of on-shell Z bosons (well-justified in off-shell region).

- ★ One of the ingredients needed to extend inclusive analysis to NLO.

- ★ At this order in the couplings, additional contributions arise from interference with tree-level background amplitudes.

- ★ Expect similar sensitivity to inclusive case.



ZZ+jet: $$\sigma^{H+I}_{off,ZZ+jet}(m_{ZZ} > 300 \text{ GeV}) = 0.0280 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.0392\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}} \text{ fb}$$

ZZ inclusive: $$\sigma^{H+I}_{off,ZZ}(m_{ZZ} > 300 \text{ GeV}) = 0.0323 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.0468\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}} \text{ fb}$$

Caveat: model dependence

- ★ The bounds on the width presented here assume that on- and off-shell couplings of the Higgs boson are the same.

- ★ This is an assumption that can be easily violated in extensions of the Standard Model that may, or may not, alter the width.

  - new heavy particles running around the loops provide a natural energy-dependence of the coupling, as new internal thresholds are crossed.

    Englert, Spannowsky: 1405.0285

- ★ The interpretation of these measurements in terms of a width constraint is therefore model-dependent.

- ★ Two interpretations:

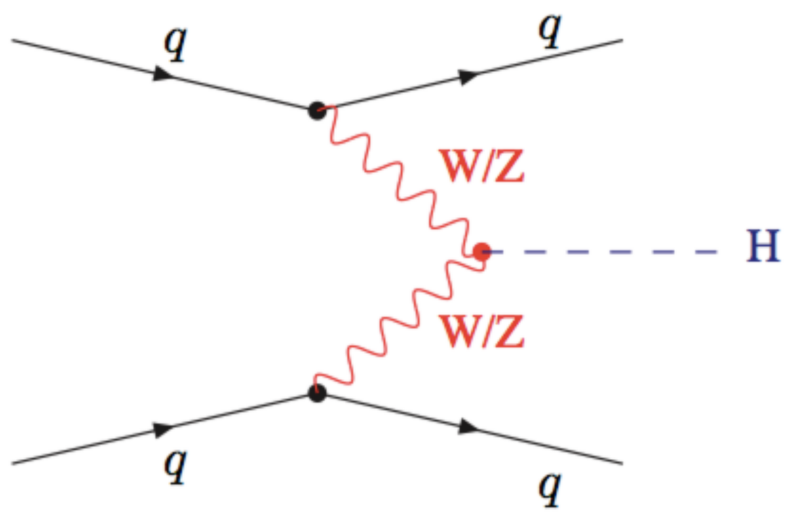
  - constraint on the width in certain classes of model, including an important consistency check of the Standard Model;

  - constraint on the off-shell coupling.

VBF channels

★ Much of the model-dependence results from possible contamination of the off-shell coupling through unknown new particles in the loops.

★ This can be alleviated by moving to tree-level processes: vector boson fusion.



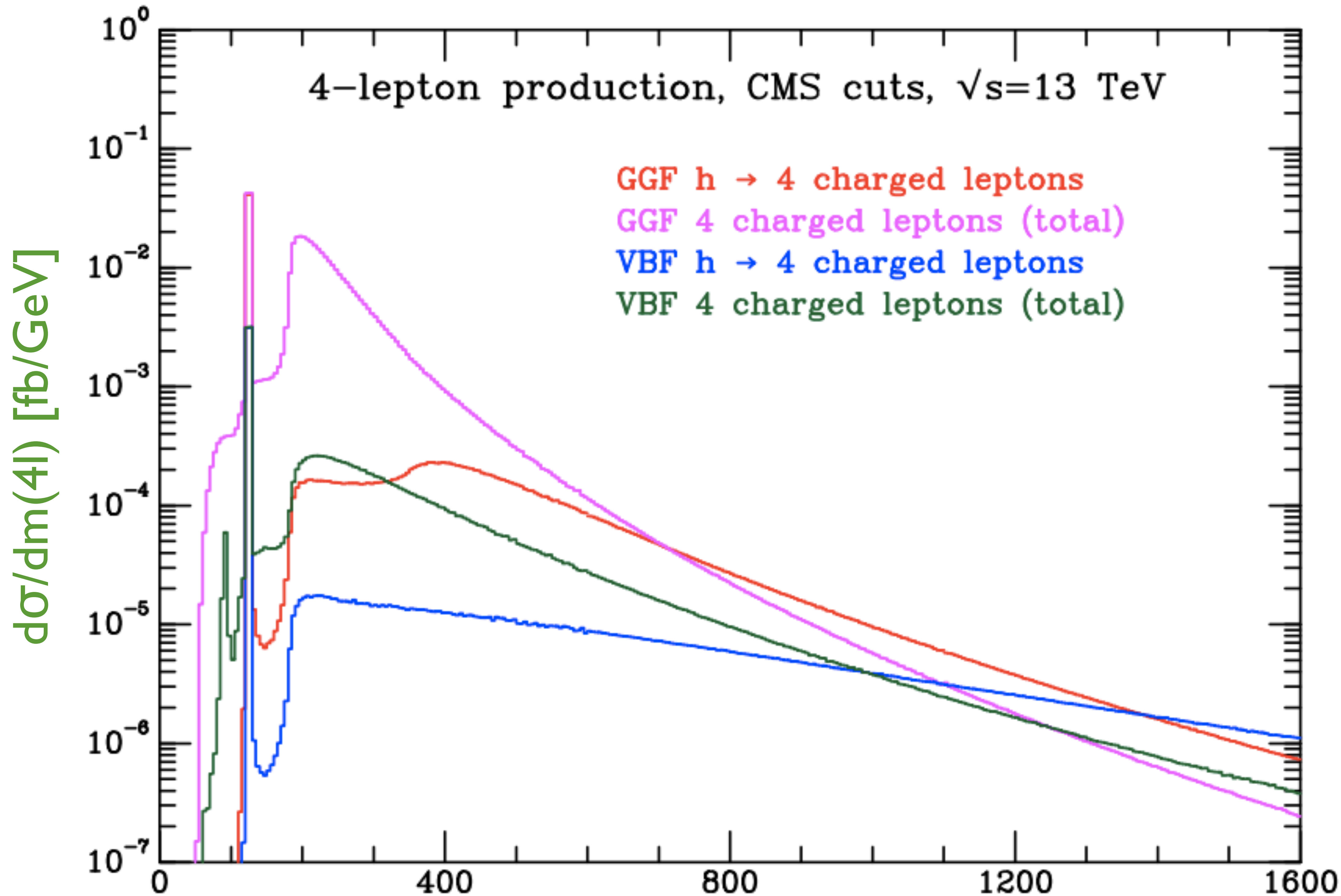
★ Of course, existing analyses receive some contribution from VBF processes already, although at a sub-dominant level.

★ VBF cross section approximately 8% of gluon fusion, will become amenable to dedicated studies in a similar vein in upcoming runs.

★ Importance of high-mass region well-appreciated for a long time due to the importance of longitudinal modes that are a consequence of EWSB.

- similar pattern of destructive interference.

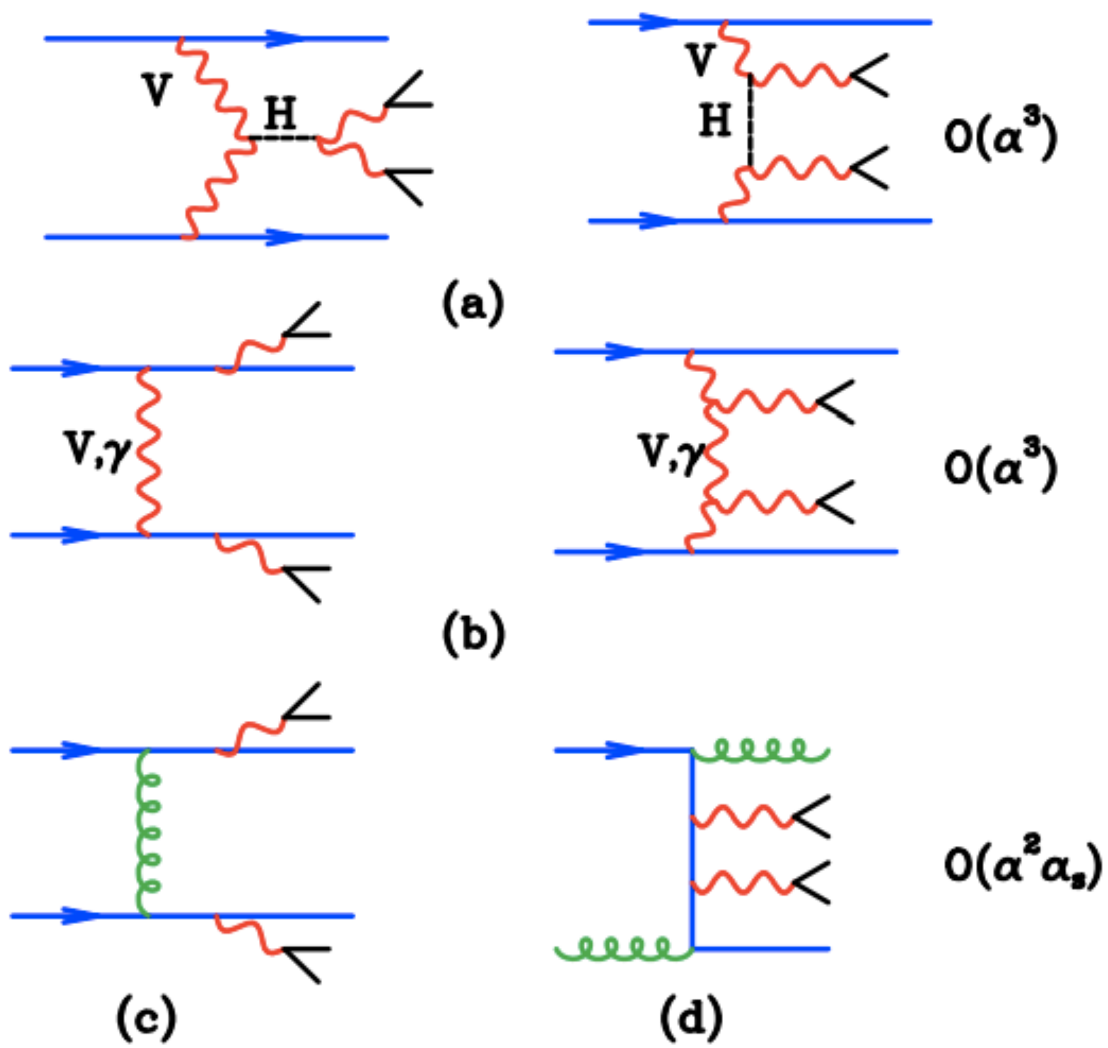
Comparison of GGF and VBF



MCFM: 1502.02990 m(4l) [GeV]

VBF and VBS

- ★ To properly treat the VBF channels, with decay of the Higgs boson into a vector boson pair VV, it is essential to include all diagrams leading to the VV+2jet state.
- ★ Here "VBF" is a loose designation, including both vector boson scattering ("VBS") contributions and all other diagrams at the same order in the couplings.



s- and t-channel Higgs (EW)

non-Higgs VV production (EW)

mixed QCD-EW

Size of rates

★ Off-shell 13 TeV cross-sections computed at LO using MCFM, in VBF-like region.

- rapidity gap between jets, opposite hemispheres, large dijet invariant mass.
- basic cuts on leptons and rudimentary cut to reduce top backgrounds.

	Events in 100 fb^{-1}	
Process	**EW process**	**mixed QCD-EW**
W	**87**	**96**
W	**27**	**2**
W	**9**	**0**
W	**20**	**37**
W	**10**	**18**
ZZ(4l)	**4**	**3**

Coupling framework

★ As before, use interim framework where H couplings to W,Z scale in same way:

$$\frac{\Gamma_{WW}}{\Gamma_{WW}^{SM}} = \kappa_V^2, \quad \frac{\Gamma_{ZZ}}{\Gamma_{ZZ}^{SM}} = \kappa_V^2$$

★ κ_V<1 better motivated theoretically, κ_V>1 corresponds to C.-M. width constraint.

★ Can be related to dimension-six operator in effective field theory:

$$\mathcal{L}_{HD} = F_{HD}\ \mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})\right]$$

$$\kappa_V = 1 + F_{HD}\frac{v^2}{2}$$

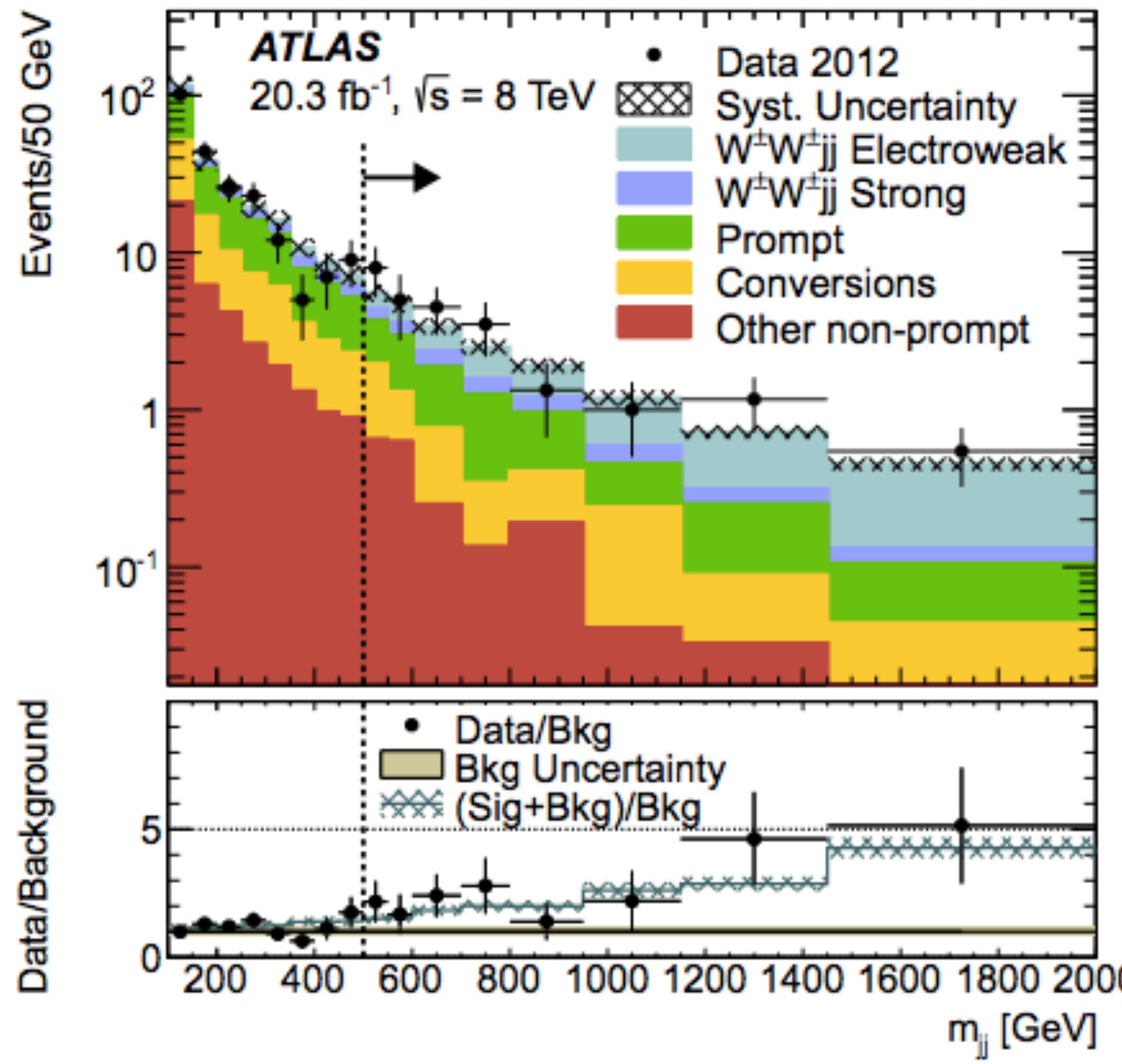
★ κ_V=0 (no Higgs boson) corresponds to F_{HD}≈30 TeV^{-2} which is outside the validity of the EFT; conversely, TeV scales correspond to a few percent deviations of κ_V.

Existing bounds

★ ATLAS has already provided evidence for same-sign W production in association with two jets.
arXiv:1405.6241

★ The expected number of events is small, so only relatively mild VBF cuts can be applied.

★ Nevertheless, the result can still be interpreted as a weak bound on the coupling strengths.



$$\kappa_V < 7.8$$

$$\Gamma_H < 60.8 \times \Gamma_H^{SM}$$

Reasonable bounds for a statistics-limited analysis in a channel without s-channel Higgs resonance!

LHC runs 2 and 3

★ Simple analysis based on Run 2 ($100fb^{-1}$) and Run 3 ($300fb^{-1}$) at 13 TeV.

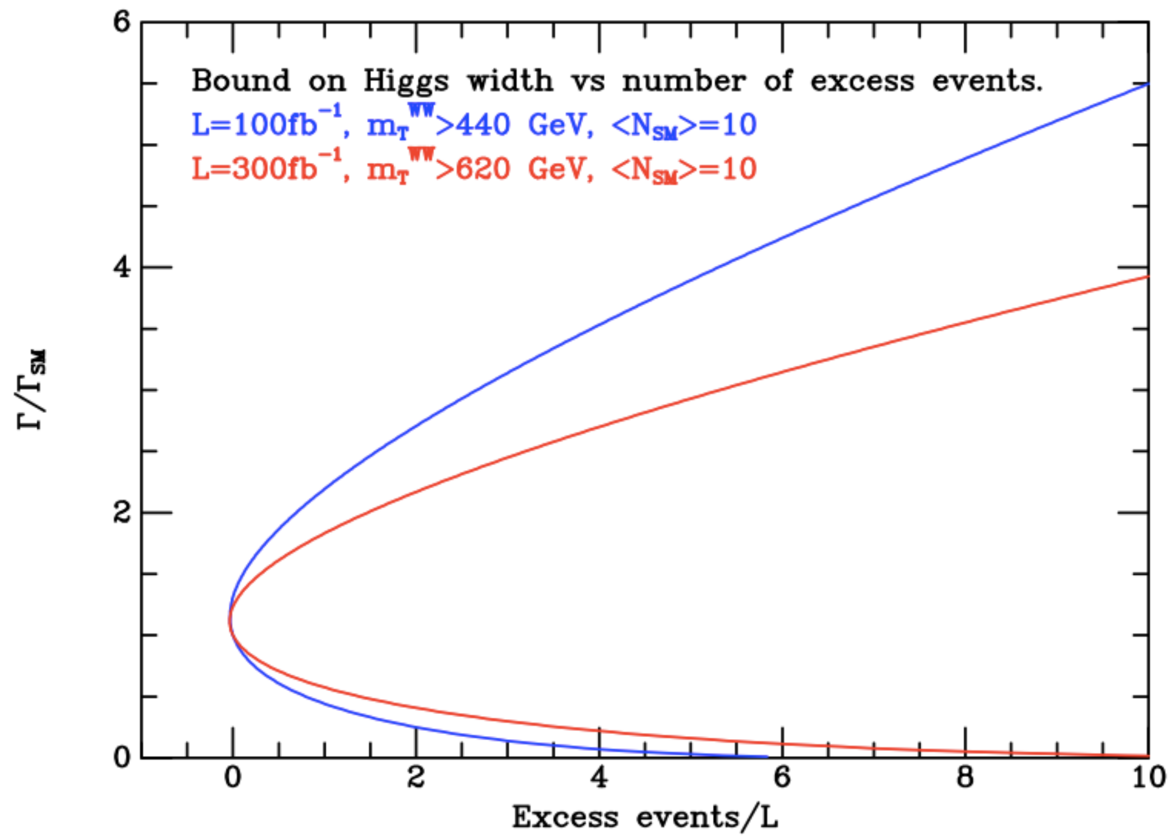
- optimize cut that determines off-shell region.
- trade-off as cut increases between better sensitivity and dwindling statistics.

★ In Run 2, only the same-sign WW process yields a lower bound on κ.

★ In Run 3, the opposite-sign W^-W^+ process may have sensitivity too (modulo handling backgrounds).

★ The same-sign processes always provide the most stringent limits, due to the lack of pollution from the mixed QCD-electroweak background.

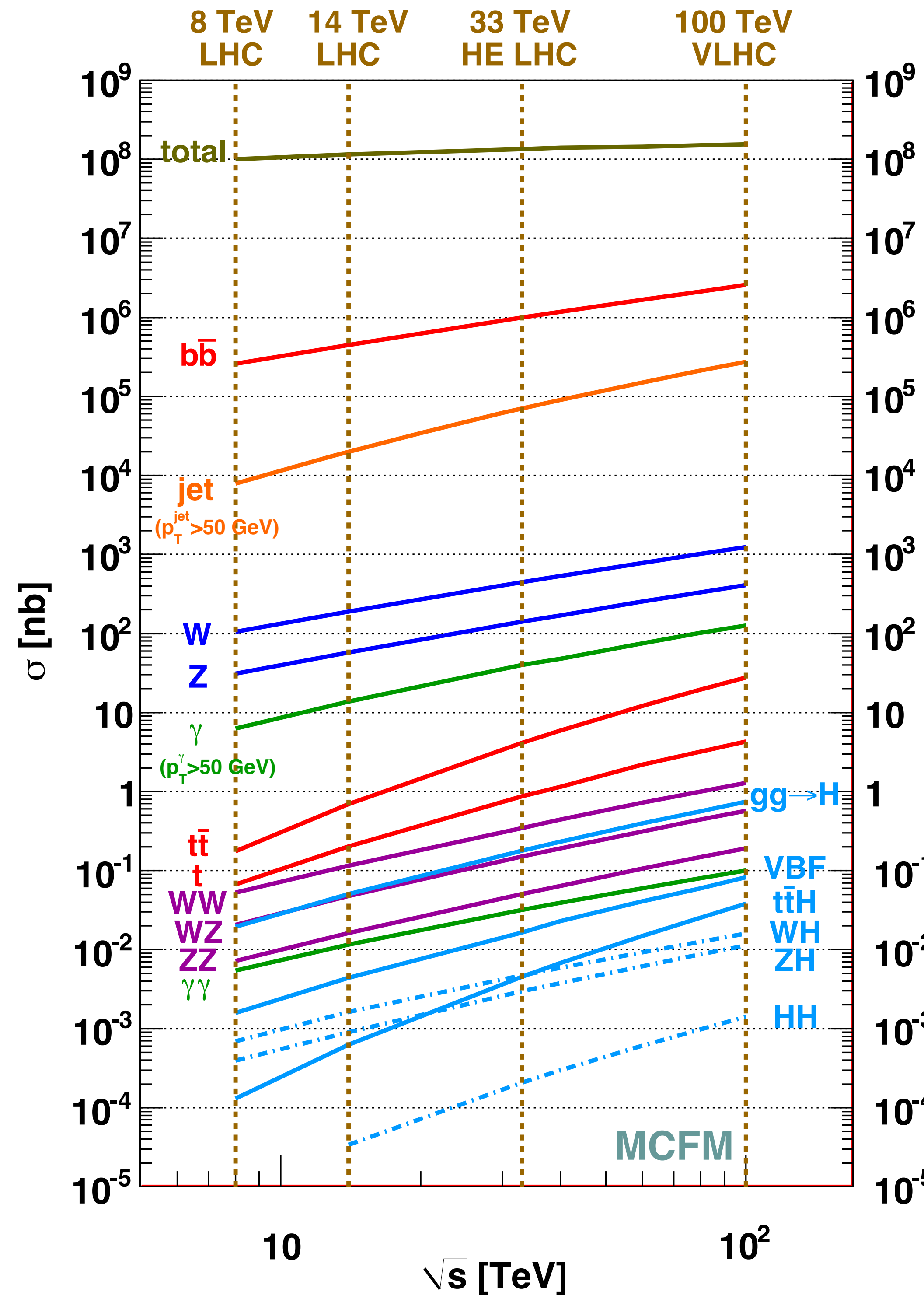
★ Sensitivity similar to GGF in Run 1.



MCFM development

MCFM: recent additions

- ★ gg→VV processes, including vector boson decays, Higgs contributions, effect of identical-particle and WW/ZZ interference.
- ★ Triphoton, diphoton+jet, four-photon production, $Z\gamma\gamma$ and $Z\gamma$+jet with photon fragmentation.
- ★ Single-top production with Higgs or Z boson (tH and tZ).
- ★ Production and decay of a top pair and a W boson (ttW).
- ★ Dark matter production with mono-jet or mono-photon signatures.

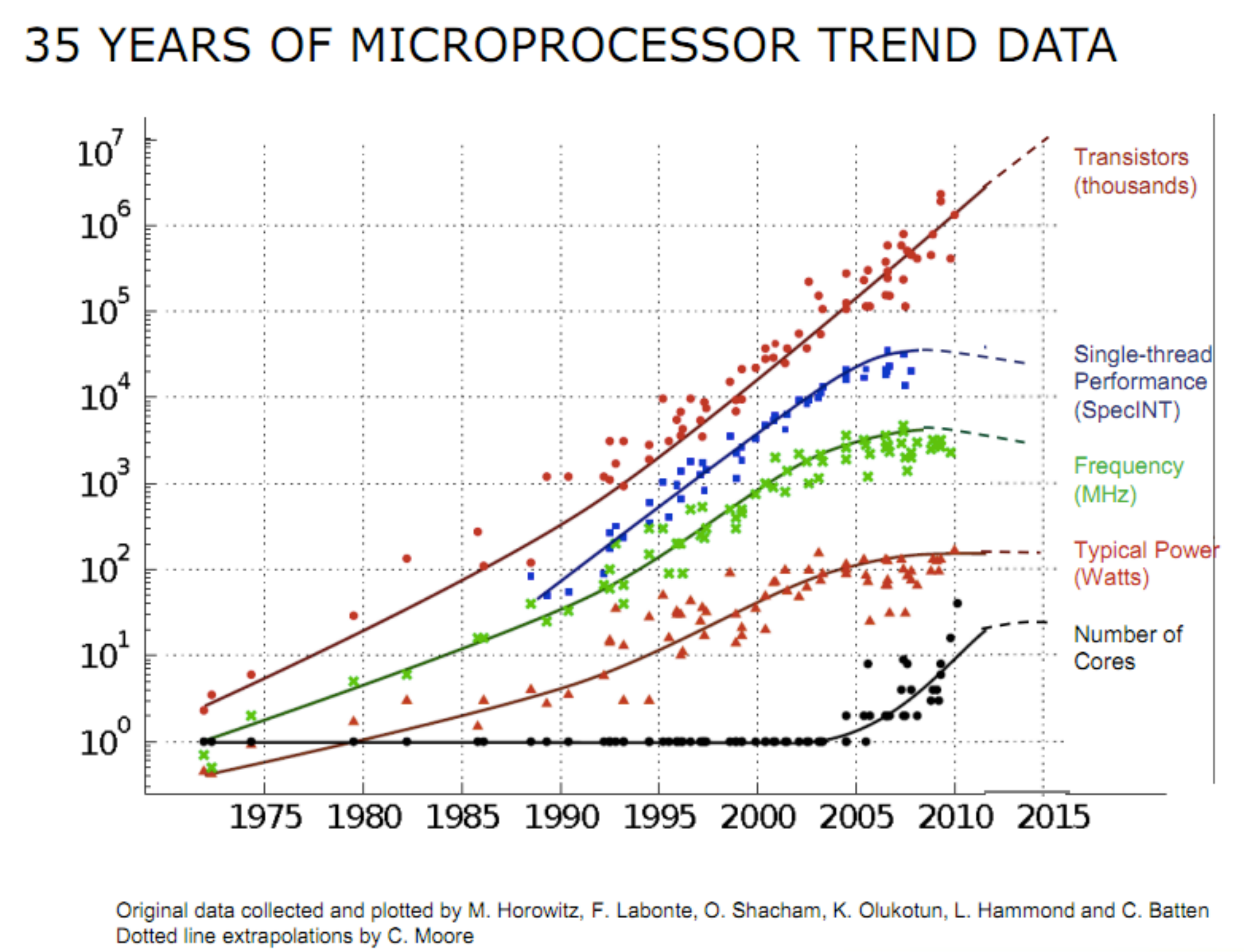


MCFM v7

- ★ Additions to the code that are coming soon:
  - multi-threaded version using OpenMP that will allow very fast generation of NLO predictions on multi-core processors.
  - evaluation of tree-level matrix elements using Berends-Giele recursion for both speed and access to high-multiplicity final states.
  - inclusion of electroweak corrections for select processes; will be completed in conjunction with Doreen Wackeroth and Jia Zhou (Buffalo).

MCFM-OMP

- ★ Continued growth in computing power (Moore's law) can only be realized by use of many parallel cores/threads.
  - imperative that HEP software can take advantage of this.
- ★ We chose the OpenMP standard to implement parallelism in MCFM
  - parallel structure is implemented using minor alterations to the code via compiler directives (comments).



- ★ Generation of many phase-space points in parallel but controlled by the same VEGAS integration parameters to obtain faster convergence.
  - care taken to ensure final result independent of number of threads used.

Speed-up example

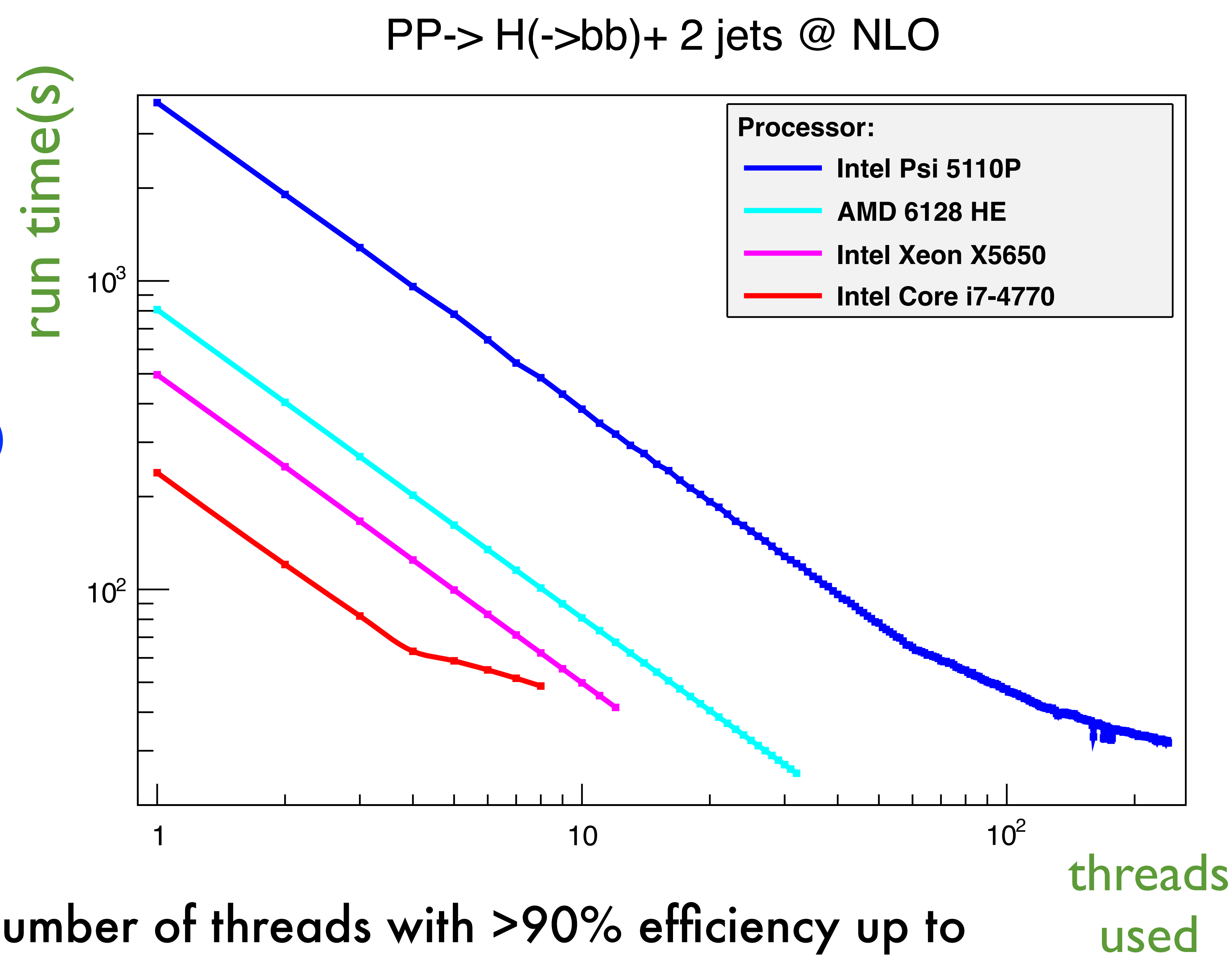
H+2 jets @ NLO: one of the most CPU-intensive calculations in MCFM

Intel Xeon-Phi (240 threads)

AMD Opteron (32 threads)

Intel Xeon (12 threads)

Intel i7 desktop (8 threads)



★ Acceleration scales with number of threads with >90% efficiency up to hardware limitations, e.g. for i7 > 4 threads, Xeon-Phi > 60 threads.

★ Single Xeon-Phi processor poor now (14x slower than single i7), but will improve.

Summary

- ★ Width and off-shell coupling bounds:
  - powerful technique that is complementary to on-shell analyses.
  - useful constraints from a number of decay modes and production channels: gluon fusion, in association with jets, VBF and VBS.
  - performing multiple analyses will provide more robust bounds and help to mitigate model assumptions and uncertainties.
  - more theoretical work remains to be done, e.g. higher-order corrections.
- ★ MCFM:
  - provides a tool for performing many of the studies discussed above.
  - development continues, with v7.0 to be released in the next couple of weeks.
  - speed gain from use of multi-cores allows more complex calculations in future.

Backup slides

Other methods for the width

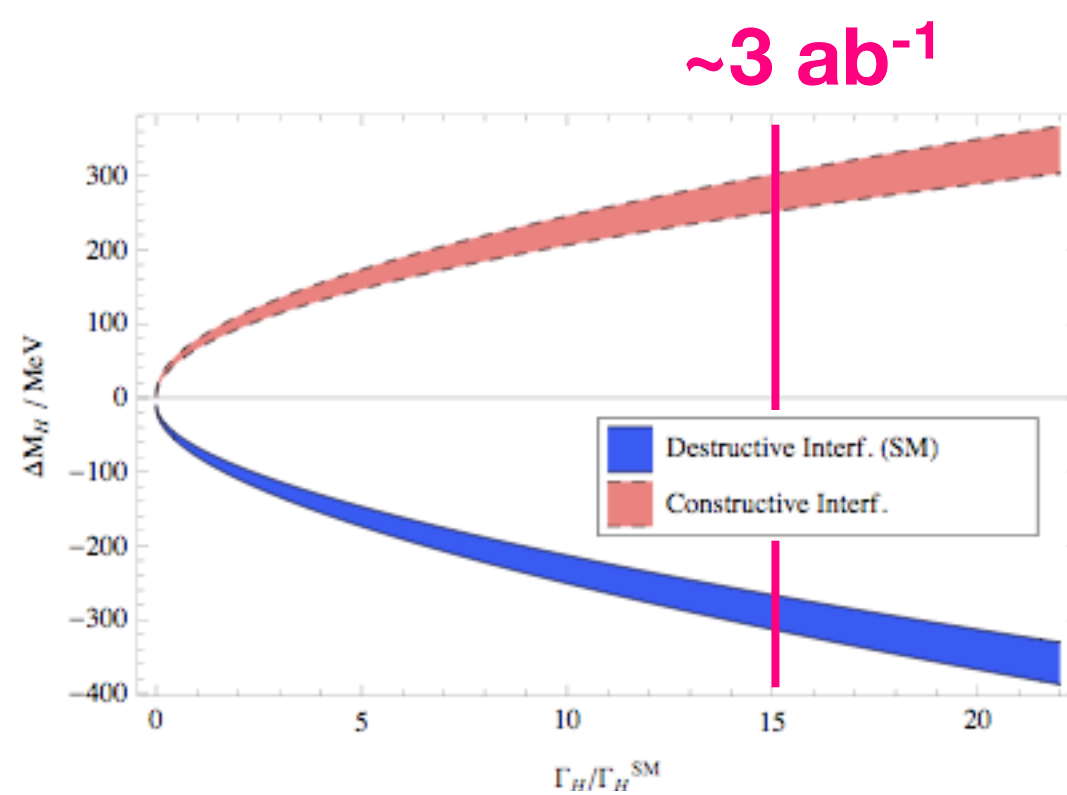
★ Direct: interferometry in diphoton decay; interference induces change in diphoton mass distribution that depends on the width.

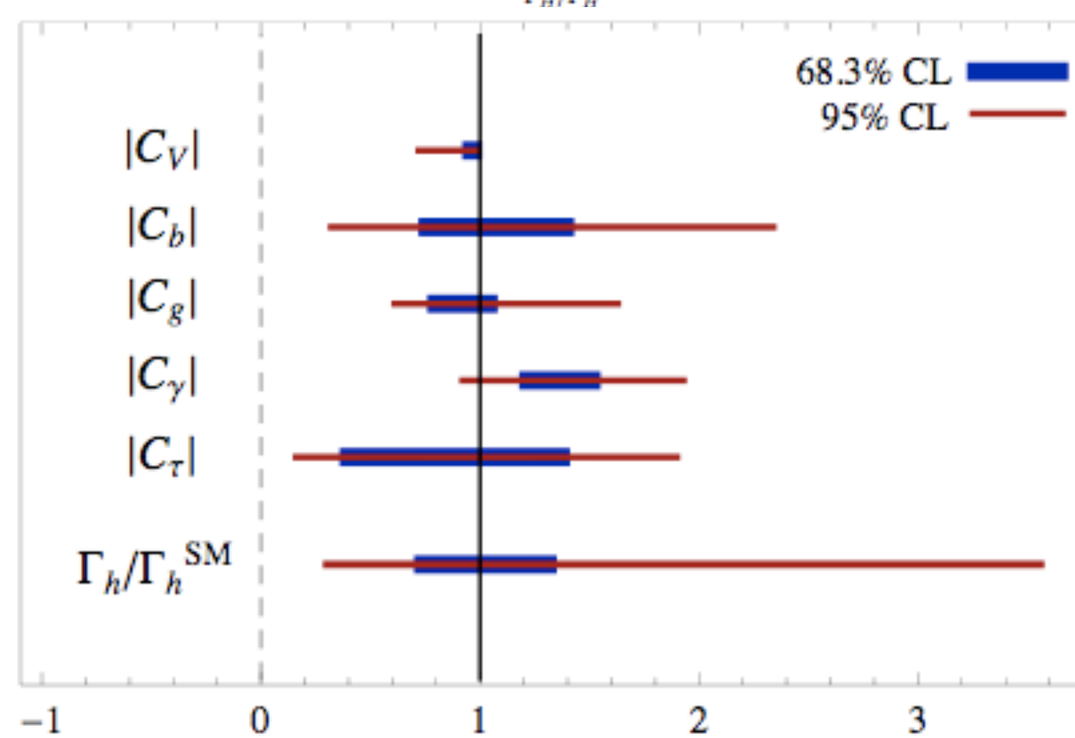
Dixon, Li; 1305.3854

★ Require precise measurement of mass shift between ZZ and diphoton channels.

★ Indirect: global coupling fits; assume either that the coupling to W,Z takes the SM value, or is bounded by reasonable theoretical assumptions.

Dobrescu, Lykken; 1210.3342

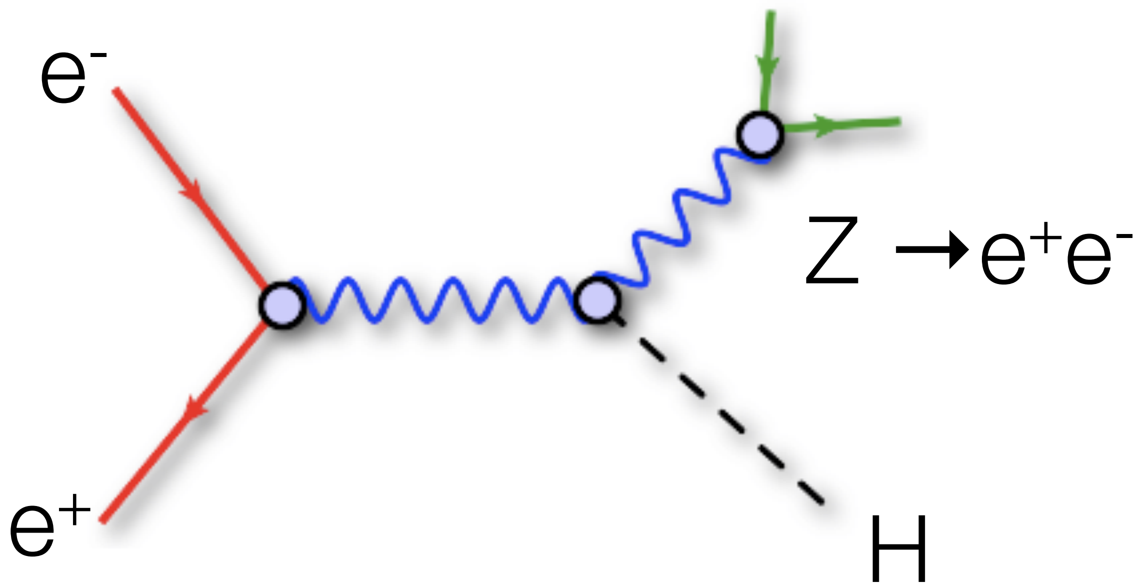




Future linear collider

★ The width of the Higgs boson is a key deliverable of future lepton colliders.

★ Clear strategy for a LC.



- Tag ZH events where recoil mass is consistent with a Higgs boson → measurement of σ(ZH)
- Measurement of H→ZZ rate then determines Br(H→ZZ)

$$\begin{aligned}\Gamma_H &= \Gamma(H \to ZZ)/\mathrm{Br}(H \to ZZ)\\ &\propto \sigma(ZH)/\mathrm{Br}(H \to ZZ)\end{aligned}$$

★ At 350 GeV and beyond (CLIC/TLEP), similar analysis through WW fusion.

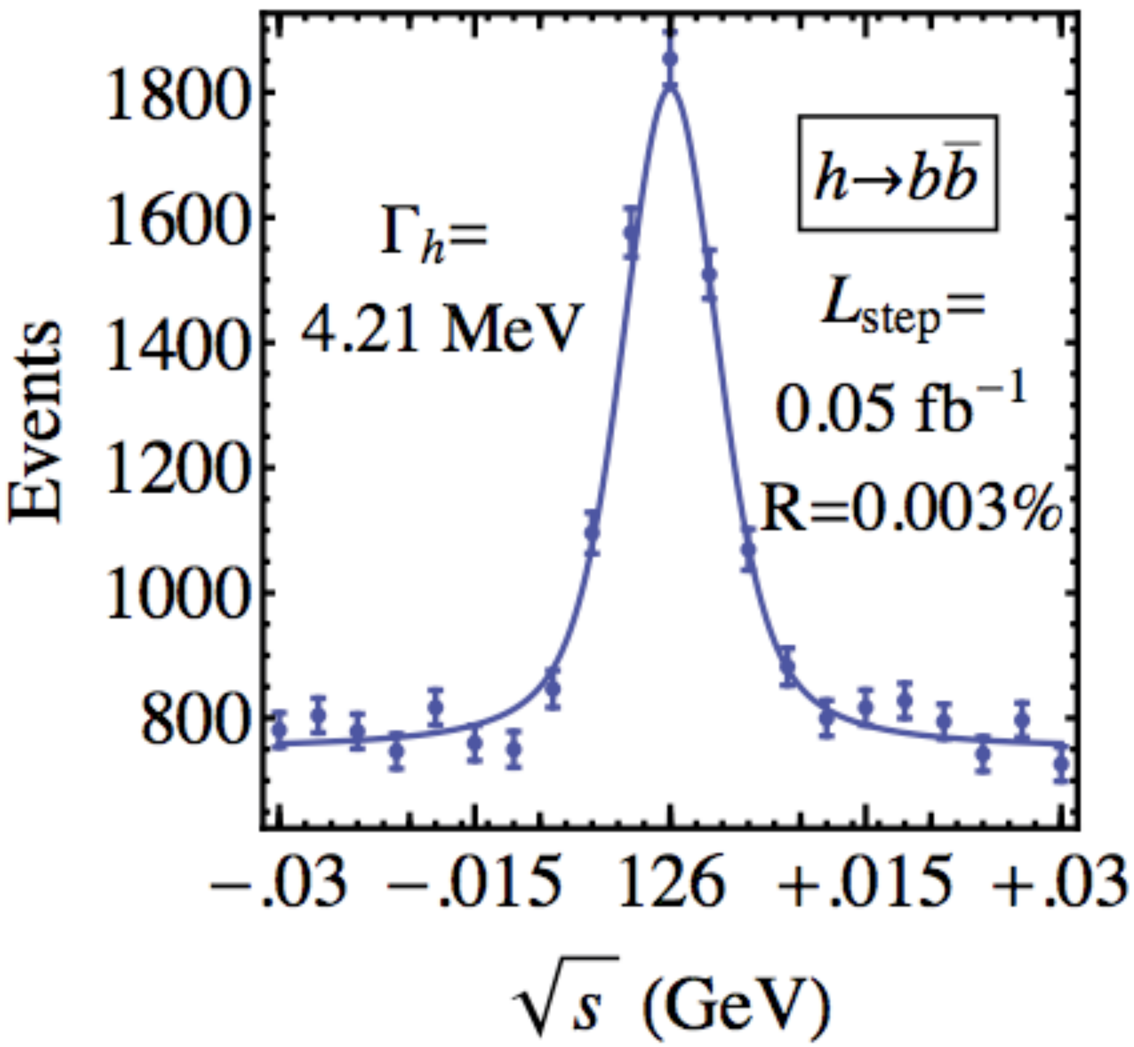
Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%

1%-10% precision

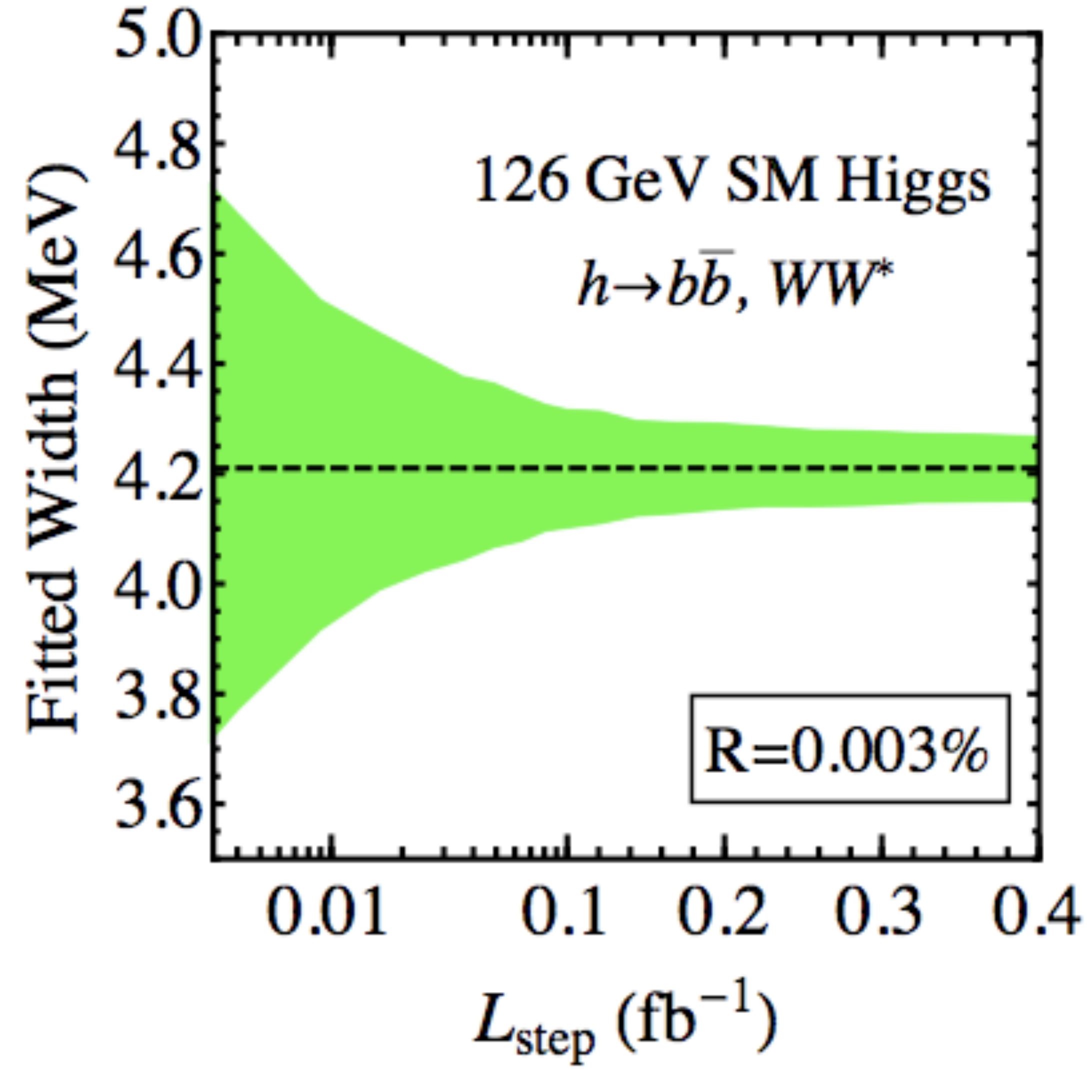
Snowmass Higgs WG,1310.8361

Future muon collider

- ★ Muon collider: direct scan of Higgs threshold.
- ★ Biggest systematic uncertainty from knowledge of muon beam.



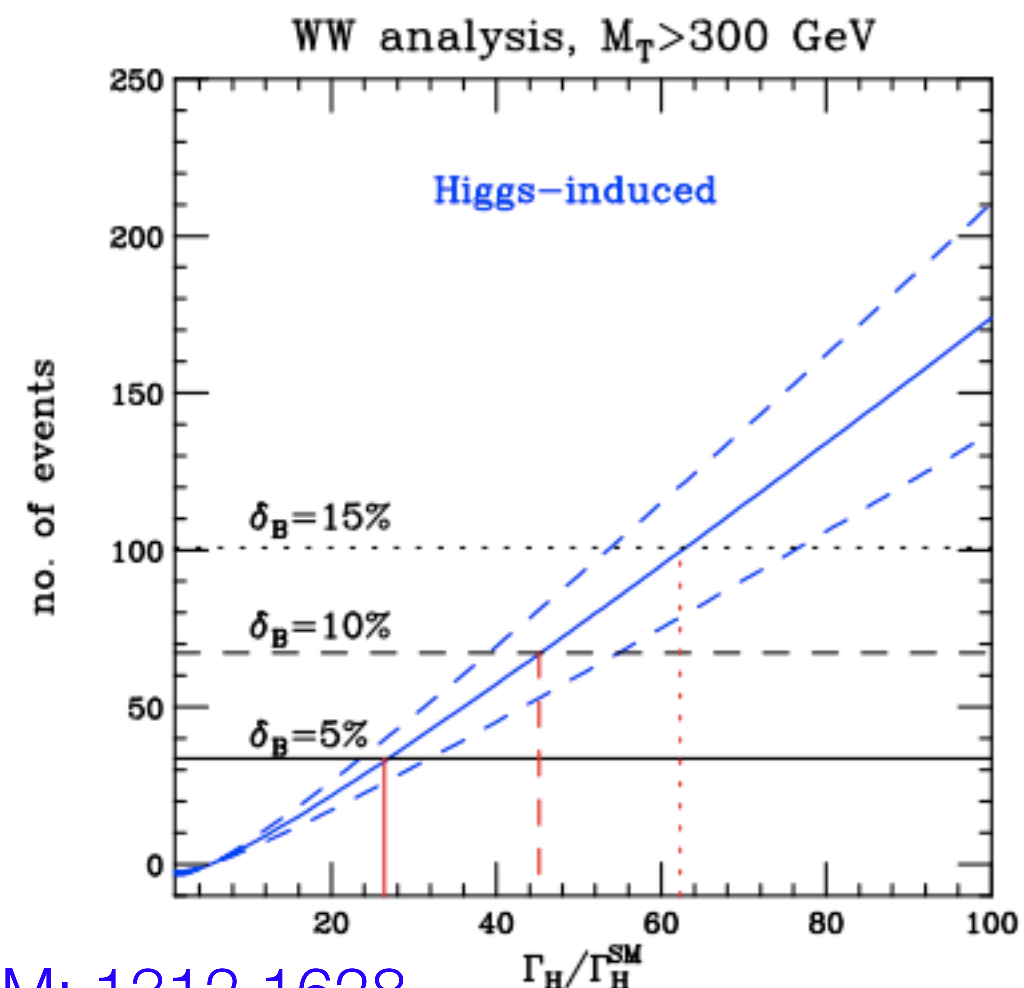
Muon collider Higgs factory study,1308.2143



~5% precision

Estimate of WW sensitivity

- ★ Usual cuts to isolate Higgs on-shell signal remove tail, so some cuts must be lifted.
- ★ Estimated sensitivity from ATLAS results, extrapolating uncertainties from on-sehll to off-shell region.
- ★ Leap of faith: extrapolation, background estimation, systematic uncertainties, ...



MCFM: 1312.1628

- <B>=336 events
- Try to be conservative by using systematic uncertainty on theory and your choice of experimental systematic uncertainties.

$$\boxed{\Gamma_H < 45^{+9}_{-7}\, \Gamma_H^{SM}}$$

- Different flavour, 20 fb^{-1}, δ_B=10%.